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THE EFFECT OF RESIDUAL STRESSES AND EXTERNAL EFFECTS ON THE FRACTURE BEHAVIOUR OF PVC PIPES

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SHORT SUMMARY

This paper describes falling-weight tests as a first step towards determining the effect of residual stresses on the fracture behaviour of old PVC-U gas pipes at impact. Results showed that the level of surrounding pipe support, the quality of the material and the diameter of the striker had a major effect on the extent of deformation and the failure mode (brittle or ductile). Due to the large scatter in the data, it could not be concluded that residual stresses had an effect on the fracture behaviour of well-supported pipes (simulating fine and well-compacted sandy soil).

KEYWORDS

Polyvinyl chloride (PVC)
Residual stresses
Falling-weight impact test
Brittle-ductile transition temperature (T_{BD})

ABSTRACT

Third-party damage is the largest cause of the failure of PVC-U pipes. Residual stresses in old PVC-U gas and water pipes were found to vary between 2 MPa and 8 MPa. The effect of these stresses on the impact resistance of PVC pipes is unknown.

The resistance of PVC pipes to external blows can be tested in accordance with ISO 3127. In practice, however, multiple external factors, including soil compaction, impact method and temperature, are relevant for the fracture behaviour of installed PVC pipes.

This study determined the so-called brittle-ductile transition temperature (T_{BD}) of PVC-U pipes by varying the temperature because failure is generally brittle in cold pipe segments and ductile in warm segments. The T_{BD} was used as a quality parameter to measure the effect of residual stresses on the impact behaviour. Pipe segments, surrounded by a tightly placed jacket pipe to simulate the soil, were impacted in the experiments using a striker.

The results showed that the level of surrounding pipe support has a major effect on the extent of deformation and the failure mechanism. Extensive deformation of the PVC-U pipe prevented failure in some cases but subsequent failure in a brittle, fragmented way also occurred. Where extensive deformation was prevented, only local failure (brittle or ductile) in the pipe segments occurred.

The quality of the material and the diameter of the striker also affected the failure mode (brittle or ductile) of the PVC-U pipe segment. The results demonstrated the difficulties associated with applying laboratory results to practice.

The excavated pipes (110 mm) had a residual stress of 3.5 - 3.8 MPa (measured using the Janson method), which is moderate. Some of these pipe segments were heated for 100 h at 60 °C to reduce the residual stress to 0.3 - 0.6 MPa.

The results showed that residual stresses – in view of the large scatter in the data – had no negative effect on the fracture behaviour of well-supported pipes (simulating fine and well compacted sand soil).

INTRODUCTION

In the Netherlands, natural gas is distributed through more than 20,000 km of rigid PVC pipes [1], otherwise known as unplasticised PVC, or simply PVC-U, pipes. Most of these pipes were installed in the 1960s when the Slochteren natural gas field in the north of the Netherlands started production.

In the next decade most of these PVC-U pipes will reach their initially specified lifespan of 50 years. Given a possible replacement surge, it is becoming increasingly important to determine the actual quality of these pipes and establish their remaining service life. If the quality is deemed to be adequate, replacement can be postponed without compromising the safety of the gas distribution grid.

An Exit Assessment programme was launched in 2004 to determine the quality of the PVC-U pipes which are still in use [2] with support and sponsorship from Netbeheer Nederland and the Dutch distribution system operators. The Exit Assessment determines the quality of the existing PVC-U material by taking samples from all over the Netherlands and subjecting them to a range of tests. A previous study introduced a new and improved tensile-impact testing method [3] that can be used to test a relatively small amount of PVC-U material at temperatures ranging from -25 °C to +47.5 °C, providing a brittle-ductile transition temperature (T_{BD}) for the PVC-U material. Although a special sawing test provided a good link with practice [3], much more work is needed to use the T_{BD} results of the tensile-impact tests to assess third-party damage to pipes in practice. More needs to be known about, for example, the effect of soil support for the pipe, the diameter of the pipe, the wall thickness of the pipe and the way of impact.

Residual stresses may be a factor of major importance. Residual stresses in old PVC-U pipes were found to vary between 2 MPa and 8.5 MPa [4]. The effect of these stresses on the impact resistance of PVC pipes is not known.

This paper describes falling-weight tests as a first step towards determining the effect of residual stresses on the fracture behaviour of PVC-U pipes at impact. During the design of an appropriate method of determining the effect of residual stresses, the effect of other test parameters were also evaluated.

EXPERIMENTAL METHOD

The resistance of PVC-HI (high-impact PVC) gas pipes to external blows must, in accordance with ISO 6993-1 [5], be tested by performing the round-the-clock test method described in ISO 3127 [6] using an adjusted striker nose. However, this method is not an appropriate way of determining the effect of residual stresses on resistance to external blows because a lot of material is needed and it is not precise enough to show clear differences in resistance. The testing method has therefore been adjusted and it is now based slightly more on the instrumented impact test [7,8].

In this new falling-weight test, a pipe segment of about 250 mm long was supported by a 120° V-shaped block. A striker with a diameter of 18.75 mm (unless stated otherwise) was dropped from a height of 739 mm, resulting in a velocity at impact of approximately 3.8 m/s, which is similar to the impact speed in the tensile-impact experiments [3] and slightly higher than in the instrumented impact test (3 m/s) [8]. The weight used was 24.53 kg (23 kg was used in the instrumented impact test [8]) to ensure an excess of energy that would result in the failure of the pipe.

The Ø110 mm PVC-U gas pipe segments were placed upon the V-block and impacted by the striker once. Three different clamping methods around the PVC-U pipe segments were used to simulate support from the surrounding soil:

1. No clamping at all: the PVC-U pipe segment was simply placed on the V-shaped block.
2. A repair clamp. Aluminium clamps of this kind are lined with rubber. The manufacturer’s instructions prescribe 32.5 Nm to install the clamp. To prevent high levels of additional stresses in the material, only 5 Nm was applied since, in this case the clamp was not being used to prevent gas leaks but merely to support the pipe.
3. A thick steel jacket pipe. The jacket pipe was 20 mm thick and it was fitted tightly around the PVC-U pipe segment without introducing much additional stress in the material. This support simulated a fine and well-compacted sandy soil.

Most of the tests were performed at room temperature, unless stated otherwise. In some tests, the pipe segments (including the repair clamp or jacket pipe) were cooled down in a refrigerator for at least 5 hours. Temperature measurements have shown that the segments with a clamp or jacket pipe had cooled down completely to the required temperature after this period of time. The pipes were then tested within 1.5 minutes to keep heating-up to a minimum.

Differences in pipe deformation were determined using a high-speed camera (240 frames per second) during impact and visually after impact (brittle or ductile failure).

Residual stresses were measured with the Janson method [9]: a strip of about 30 mm wide was cut from a ≥110 mm long pipe segment. The width between the two cut surfaces was measured after three minutes. The residual stresses were calculated on the basis of the diameter, the wall thickness and the bi-axial creep modulus of PVC-U (3500 MPa).

To reduce the residual stresses, PVC-U pipe segments were placed in an air oven at 60 °C for one week.

RESULTS AND DISCUSSION

Effect of the clamping method

The way PVC-U pipe segments were supported had a major impact on the results in the falling-weight tests. Three segments were tested of the same PVC-U pipe supported by three different clamping methods, as described in the experimental section. The difference was most clearly seen in the stills taken with the high-speed camera (Figure 1 to Figure 3). The stills show the point in time at which the largest deformation occurred. The next frame shows either less deformation because the striker has bounced back up, or fracture of the PVC-U pipe segment. Figure 4 to Figure 6 show stills taken with the high-speed camera a few frames after the largest deformation occurred.

The stills demonstrate that enormous deformation is possible in PVC-U pipes when there is no surrounding support (Figure 1). This dissipates a lot of the energy introduced by the striker. Without any support from the surrounding environment (such as the soil), there was no fracturing of the investigated pipes (Figure 4).

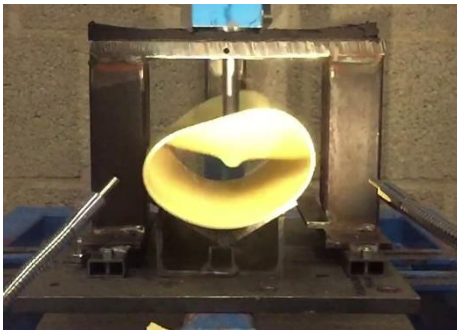

Figure 1. The PVC-U segment is completely free to move and able to withstand a major impact, because it can deform. The segment does not fail.

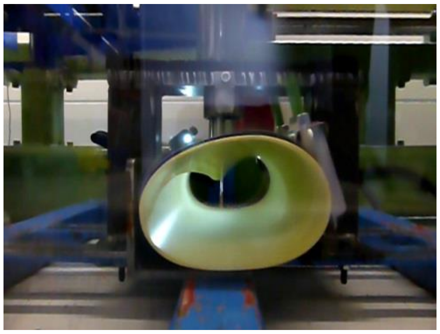

Figure 2. Movement of the PVC-U segment is restricted by the repair clamp. There is not enough deformation to dissipate the energy and to prevent failure (this has not yet occurred in this frame).

Figure 3. Deformation of the entire PVC-U segment is prevented by a thick steel jacket pipe. Brittle failure is inevitable (this has not yet occurred in this frame). The PVC can deform locally around the striker.

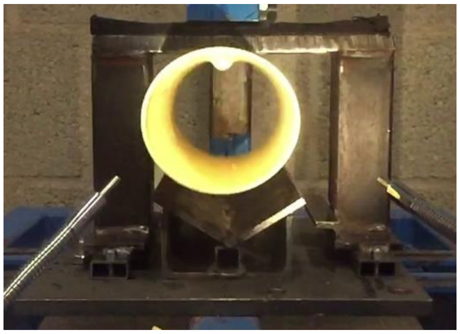

Figure 4. A few frames after Figure 1. The PVC-U segment does not fail and bounces back up from the V-shaped block.

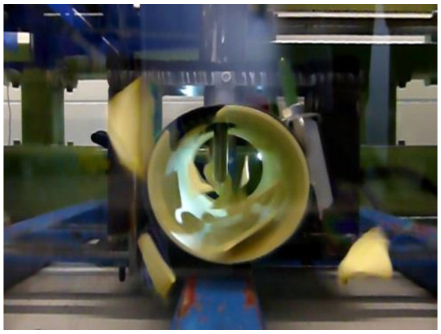

Figure 5. A few frames after Figure 2. The entire PVC-U segment shatters in a brittle way.

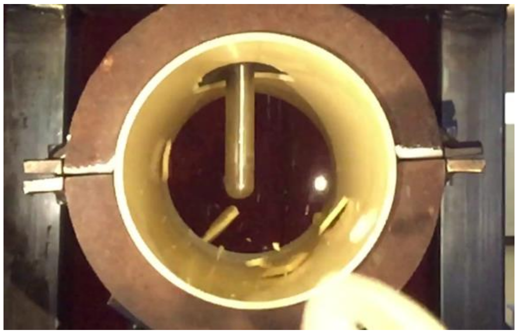

Figure 6. A few frames after Figure 3. There is local brittle failure only.

It is known that pipe dimension is a major determinant of deformation. A large pipe can withstand a much larger impact than a smaller pipe because the forces are distributed over much more material. A thin-walled pipe will deform much more easily than a thick-walled pipe.

If the elastic deformation of the pipe is hindered by, for instance, the surrounding soil or by a repair clamp as here, more energy is concentrated around the striker (Figure 2). The pipe segment therefore fails in a brittle way. The failure was not only concentrated around the striker. Because deformation occurred over a larger area, the segment shattered (Figure 5).

When elastic pipe deformation was completely eliminated by the thick steel jacket pipe, deformation was very localised (Figure 3). Failure occurred very locally around the striker (Figure 6), resulting primarily in the testing of the material rather than the complete deformation of the pipe.

These results adequately demonstrate the difficulty of applying the absolute brittle-ductile transition temperature (T_{BD}) from tensile-impact tests to practice. The tensile-impact tests use test bars and disregard global pipe deformation, because only deformation on a local scale can be assessed. The amount of deformation is highly dependent on support from the surrounding soil. Support from the soil can vary considerably depending on factors such as the soil type and variations in soil compaction.

These results show that the pipes surrounded by the supporting soil are particularly susceptible to third-party damage. The impact resistance of the pipes increases when the soil around the pipe is removed.

To determine the effect of residual stresses on impact resistance, it was decided to continue with further experiments using the steel jacket pipes. There were two main reasons for this decision.

Firstly, the steel jacket pipe prevents large variations that may occur with other clamping methods. The scope of this research did not include the precise simulation of the surrounding soil. At this stage of the research, it was interesting to determine the effect of residual stresses on the material alone, but still in pipe form, rather than using test bars as in the tensile-impact tests.

Secondly, at this stage of the research, it proved no longer possible to produce a difference in failure due to temperature (brittle at low temperatures and ductile at high temperatures). The PVC-U segments without any clamping, for example, did not fail at all. It is therefore difficult to determine the effect of residual stresses. If neither a segment with high residual stresses nor another segment with low residual stresses fails, it is impossible to determine the effect of residual stresses.

Effect of the material

It is clear that the clamping method plays a major role. However, the quality of the material should not be underestimated as a factor. In the initial tests with the selected PVC-U pipes, only brittle fractures were observed when the segments were supported by the repair clamp. However, in a few exploratory tests using a different PVC-U pipe, this pipe failed in a ductile way when the test parameters were identical (compare Figure 7 and Figure 8). In this case, the difference in failure behaviour upon impact was caused only by a difference in the quality of the material. This result obviously concurs with practice, where some pipes shatter and other pipes do not fail at all in similar conditions.

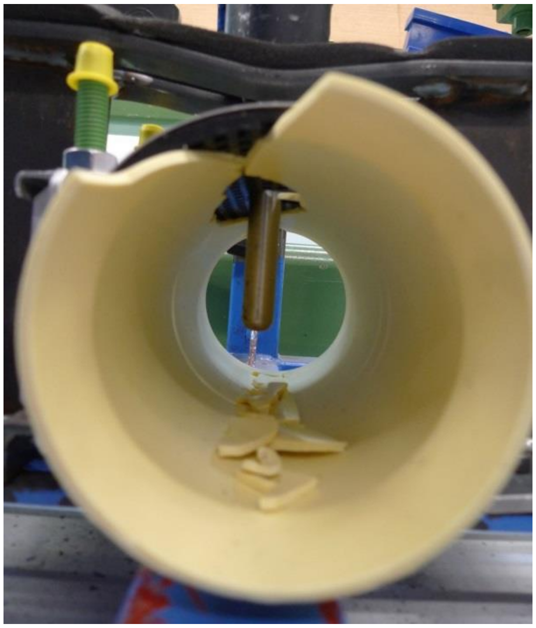

Figure 7. Brittle failure of a PVC-U segment surrounded by the repair clamp.

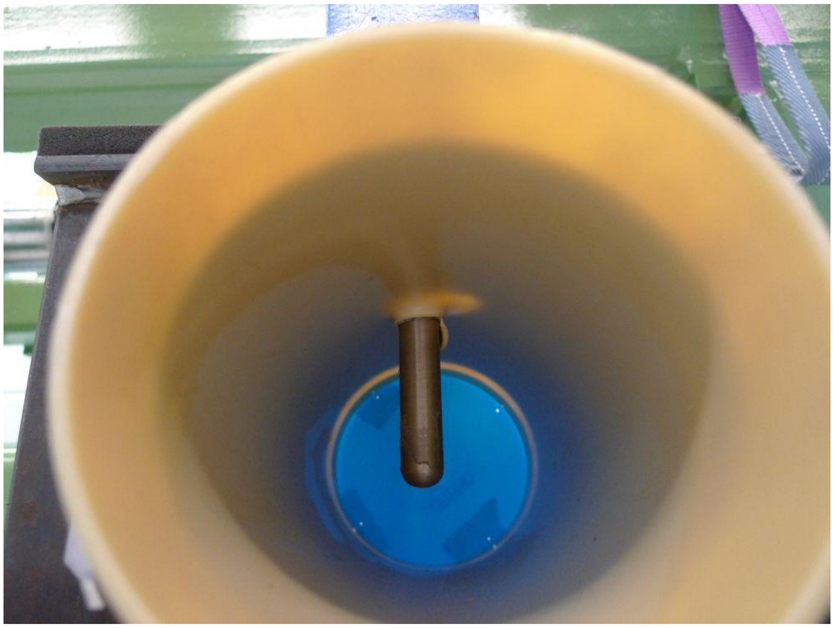

Figure 8. A different PVC-U pipe failed in a ductile way, when the test parameters were exactly the same as in Figure 7.

Effect of the striker diameter

When the thick steel jacket was used, only brittle fractures were observed in the selected PVC-U pipe segments at room temperature. Since the aim was to obtain a brittle-ductile transition temperature, this high temperature should in fact have led to ductile failure. In this case, the temperature could have been lowered to find the temperature at which brittle failure would occur, identifying a specific transition temperature.

The striker diameter was therefore reduced from 18.75 mm to 8 mm. In this case, it was possible to induce ductile failure in the selected PVC-U pipe (Figure 10) because the stresses are absorbed by a much smaller surface area. This was also observed in the extent of local deformation just before failure, which was much less when the 8 mm striker was used by comparison with the original striker (compare Figure 9 with Figure 3).

It is important to realise that a smaller striker leads to a ductile failure but that it will also penetrate materials more easily. In this research, excess energy was used to ensure failure. If this amount of energy is reduced, it is entirely possible that the PVC-U pipe will not fail at all with the original striker but that it will do so when the smaller striker is used. Once again, this demonstrates the complexity of applying laboratory results to practice. In the field, ‘strikers’ associated with third-party damage are not well defined and they do not always strike the pipe perpendicularly, leading to complex stress distributions and deformations.

Figure 9. Still made with a high-speed camera just before failure. There is hardly any local deformation in the PVC-U pipe segment around the small striker (compare with Figure 3).

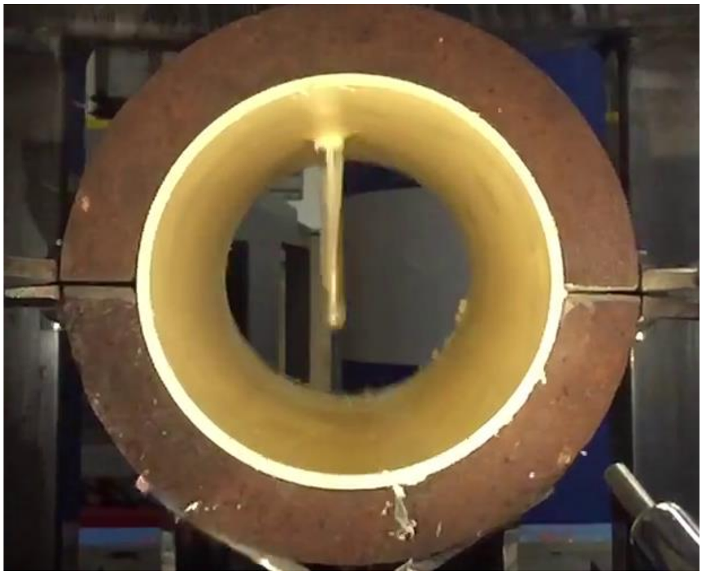

Figure 10. The PVC-U pipe segment fails in a ductile way when a smaller striker is used (compare with Figure 6).

Effect of temperature

A ductile failure was obtained at room temperature when using the smaller striker. The next step was to determine whether a lower temperature would result in brittle failure, making it possible to determine a brittle-ductile transition temperature.

The selected PVC-U pipe failed in a brittle way at about 5 °C using the smaller striker (Figure 11 and Figure 12). This means that the brittle-ductile transition temperature can be determined for pipes with high residual stresses and low residual stresses (see below).

Effect of residual stresses

The PVC-U pipes selected originally had a residual stress of approximately 3.5 - 3.8 MPa, as determined using the Janson method [9]. After tempering of the pipes in the oven, the residual stresses decreased to about 0.3 - 0.6 MPa. A total of 38 original pipe segments and 30 oven-tempered pipe segments were tested at between 9 °C and 23 °C with the smaller striker (8 mm), using the thick steel jacket pipe as surrounding support. At least two segments were tested at each degree Celsius and the failure mode (brittle or ductile) was then determined visually.

Figure 11. Still made with a high-speed camera just before failure. As at room temperature, there is hardly any local deformation of the PVC-U pipe segment at 5 °C around the small striker (Figure 9).

Figure 12. The PVC-U pipe segment fails in a brittle way when a smaller striker is used at 5 °C (compare with Figure 10).

Table 1 lists the results for the different failure modes. The first thing to notice is the large scatter in failure mode at a range of temperatures. This is not necessarily due to the test method. Considerable efforts were made to prevent scatter associated with the testing method. For instance, the cooling time for the pipe segments was identical for each segment, the same steel jacket pipe was used for every pipe segment, the position on the V-shaped block was accurately aligned for every segment and the striker tip was checked and polished if needed after every impact. Much of this scatter is therefore caused by the lack of homogeneity in the PVC-U material itself, which has also been observed in other studies [3,8]. This inevitable scatter hampers the interpretation of the results.

The brittle-ductile transition temperature (T_{BD}) and the average variation for the results was calculated. These results are shown at the bottom right of Table 1. The extent of the variation found around T_{BD} (T_{min} and T_{max}) was normal compared with the tensile-impact tests.

Note that T_{BD} was determined for one pipe only with a specific quality using one type of clamping and one striking method. Varying one of these test parameters will result in a different T_{BD}. The results found in this research should be seen as tendencies. Absolute transition temperatures cannot be applied to other test methods or practice. This would require further research.

The results in Table 1 show that there is no difference between the T_{BD} of the original pipe segments with relatively high residual stresses and the tempered pipe segments with low residual stresses. This indicates that in this test set-up, the residual stresses do not affect the failure behaviour of PVC-U pipes.

Table 1. Failure mode of PVC-U pipes (original pipe with 3.5 -3.8 MPa residual stresses and tempered pipes with 0.3 -0.6 MP residual stresses) in the falling-weight tests at different temperatures. Red indicates brittle failures only at the given temperature, yellow indicates both brittle and ductile failures at the given temperature are found and green indicates ductile failures only at the given temperature. The calculated brittle-ductile transition temperature (T_{BD}) is given in the bottom-right corner. "n.t." indicates that this segment is not tested.

Temperature (°C)	Original pipe	Tempered pipe
9	brittle	brittle
	brittle	brittle
10	brittle	ductile
	brittle	brittle
11	ductile	brittle
	brittle	brittle
12	brittle	brittle
	brittle	brittle
	brittle	n.t.
13	brittle	brittle
	brittle	ductile
	ductile	n.t.
14	ductile	ductile
	brittle	brittle
	ductile	n.t.

Temperature (°C)	Original pipe	Tempered pipe
15	brittle	brittle
	ductile	ductile
	ductile	n.t.
16	ductile	ductile
	brittle	ductile
	brittle	n.t.
17	brittle	brittle
	ductile	ductile
	ductile	n.t.
18	brittle	ductile
	ductile	brittle
	brittle	n.t.
19	brittle	ductile
	brittle	ductile
	ductile	n.t.

Temperature (°C)	Original pipe	Tempered pipe
20	brittle	ductile
	ductile	ductile
	ductile	n.t.
21	ductile	ductile
	n.t.	ductile
22	ductile	ductile
	n.t.	ductile
23	ductile	ductile
	ductile	ductile
	ductile	n.t.
T_{min}	**13.4°C**	**11.9°C**
T_{BD}	**16.0°C**	**14.5°C**
T_{max}	**18.6°C**	**17.1°C**

Attention should be drawn here to one important consideration. The thick steel jacket pipe prevented the deformation of the entire pipe so that only local deformation was possible. The advantage was that only the material in pipe form was tested. The results indicate that residual stresses do not have any effect on the material behaviour. However, it is entirely possible that the residual stresses do affect the deformation of pipe, a factor which was not taken into consideration in the test set-up that was used.

Future research should compare deformation of the entire pipe with relatively high residual stresses and with low residual stresses upon impact at various temperatures.

CONCLUSIONS

Results showed that the level of surrounding pipe support had a major effect on the extent of deformation and the failure mode (brittle or ductile). Extensive deformation of the PVC-U pipe prevented failure in some cases, but subsequent failure in a brittle, fragmented way also occurred. The prevention of extensive deformation led only to local failure in the pipe segments.

The quality of the material and the diameter of the striker also affected the failure mode (brittle or ductile) of the PVC-U pipe segment. The results demonstrate the complexity of applying laboratory results to practical situations.

Heating pipe segments to 60 °C for 100 h reduced the residual stresses from 3.5 - 3.8 MPa to about 0.3 - 0.6 MPa. The results show that residual stresses – in view of the large scatter in the data – did not have a negative effect on the fracture behaviour of well-supported pipes (simulating fine and well compacted sand soil).

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