Evaluation of surge and fatigue resistance of poly(vinyl chloride) and polyethylene pipeline materials for use in the UK water industry

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The current advice for design against fatigue in water and sewerage pipelines contained in the Pipe Materials Selection Manual was adopted from BS CP312, which was introduced owing to concern about large numbers of failures of unplasticised poly(vinyl chloride) (uPVC) pipelines in the 1960s and 1970s. Although originally intended for uPVC alone, the derating criteria were also adopted in the Pipe Materials Selection Manual for polyethylene (PE) materials. There have been no reported fatigue failures in PE pipelines and failure rates for uPVC pipes have declined markedly in the last few years, largely because of increased static fracture toughness.

It is now believed that this design advice is excessively conservative. A research programme has been undertaken to determine the fatigue resistance of the range of PE and PVC materials currently used by the water industry, taking into account the many variables encountered. Modern PE80 and PE100 materials have been shown to be highly resistant to premature failure by cyclic loading and providing they pass water industry toughness criteria do not require derating. However, those PE materials that have not been demonstrated to satisfy the water industry specifications and all types of PVC pipes should be derated by different factors developed from extrapolation of data for each material. The research has led to the development of new fatigue design factors and separate surge pressure ratings for the various PE and PVC pipeline materials, forming the basis of a new Information and Guidance note (WIS 4-32-07) for the water industry. PRCPA/1536

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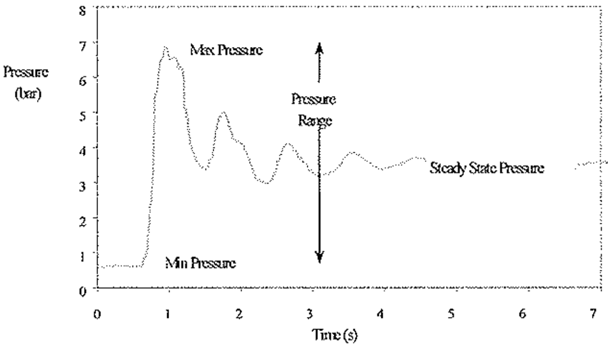
INTRODUCTION

Many early brittle failures in poly(vinyl chloride) (PVC) water and sewerage pipelines, where repeated surge events are thought likely to induce embrittlement, were attributed to fatigue. The concerns of pipeline engineers led to the adoption of the British Standard Code of Practice CP 312 by the UK water industry,[1] which gives maximum and minimum pressure ratings for various pipe classes.

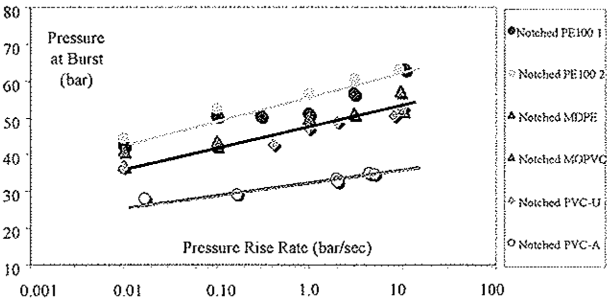
'Surge and fatigue' are often combined as a collective term. However although both phenomena arise from the same events (valves closing quickly, pump shutdown, etc.) they should be considered separately since they describe different effects on the pipe material. Rapid closure of a valve or a pump starting up may give rise to a rapid increase in pressure to a level well in excess of the steady state condition. This is commonly known as surge. Surge 'events' generally occur over a very short timescale and it is known that many unplasticised (u)PVC pipe failures followed surges in pressure in pumped systems. Fatigue is associated with the repetition of such events, where the fluctuations in pressure cause a loss in the long term strength of the pipe material.

Because it was believed that the combined effect of over pressurisation from surge and loss in properties caused by fatigue could have serious implications on the lifetimes of uPVC pipelines, a design code was introduced in 1977 (BS CP312). The advice for design from both CP312 and the Pipe Materials Selection Manual (PMSM) is that in a dynamic loading situation, the difference between maximum and minimum pressures must be less than 0·5 × the static rating. An additional criterion is that the maximum pressure must always be less than the pipe rating. In many pumping situations, the maximum pressure may increase to × 2 the steady state condition and decrease to zero. This means that the stress range is twice the static case and hence via CP312 criteria, the wall section must be increased by a factor of four. Increasing wall sections of pipes has clear cost implications, since the cost of plastics is directly proportional to the weight of material used. It is also well known that increasing wall thickness promotes the generation of a state of plane strain in the wall section and this will reduce resistance to crack growth under static loading.

The water industry adopted the CP312 code for uPVC in the PVC Guidance Manual and the Water Research Centre extended the range of materials affected to include polyethylene (PE) pipe materials in the PMSM. There was no service evidence to suggest that fatigue was a problem for PE; the criteria were adopted as a conservative measure awaiting experimental evidence to demonstrate whether the properties of PE are affected by cyclic loading. Since there is also considerable evidence to suggest that the major problems with uPVC were associated with



1 Typical pressure fluctuation from sudden valve closure in PE SDR11 pipe



2 Effect of pressure increase rate on strength of plastics pipes

static overloading rather than fatigue, clarification of the UK design position was sought by the water utilities. Laboratory research on the fatigue of PVC and PE materials has thus been carried out by Pipeline Developments via a commission from UK Water Industry Research Ltd, to define the position for the range of tough polymers currently in use in the UK water industry.

Defining surge

In a pumped system, the most frequent events that cause unsteady variations in pressure are pump startup and shutdown. Secondary events such as air and line valves opening and closing could also generate pressure excursions. Generally, it is the fast closing of valves and uncontrolled pump shutdowns that cause the most severe changes and oscillations in pressure.[2]

Surge creates fluctuations in pressure about the steady state level. The initial rate of pressure change is very high but of short duration. The fluctuations decay rapidly. An extreme pressure fluctuation trace caused by the instantaneous closing of a solenoid valve on a 25 mm PE pipe is shown in Fig. 1. For larger distribution and branch mains, the increase rates will be lower but nevertheless, the peak pressure may be considerably in excess of the steady state case, and the minimum value may be subatmospheric. Many engineers fear that extremes of both high and low pressure may cause damage and that high pressure peaks may cause pipe rupture.

It should be noted that the stiffness of plastic pipes is lower than for metal/asbestos cement pipes and thus the pressure shock wave transmission speeds are lower. Hence, the pressure increase rates and peak levels will be much reduced. It is important that designers conducting hydraulic simulations use the correct short term modulus for each material, so that realistic results are obtained.

Response of thermoplastics to high rate loading

Thermoplastics such as PVC and PE respond to high rates of loading by exhibiting greater strength and stiffness, since the entangled molecular structure of the materials provides resistance to deformation. At high pressurisation rates, pipes are better able to resist the higher stress levels generated by surge. In addition, the strength of both materials will increase with high rates of loading.

Tests have been made on various PVC and PE pipes in which the pressure was increased at different rates until failure occurred. All the pipes were prepared by machining 100 mm long sharp notches into the external surfaces, penetrating to 10% of the wall section. This simulates the situation that may occur because of damage imposed during handling and installation. The data are shown in Fig. 2 where pressures at failure for PVC and PE pipes of different static pressure ratings are given as a function of loading rate.

The burst test data show that at pressure increase rates typically occurring in surge events (0·1–10 bar s^{-1}), all PVC and PE pipes have strengths well in excess of their respective static stress ratings. Thus, for these materials, the rapid increase in pressure that is the characteristic of surge is not necessarily a significant practical problem.

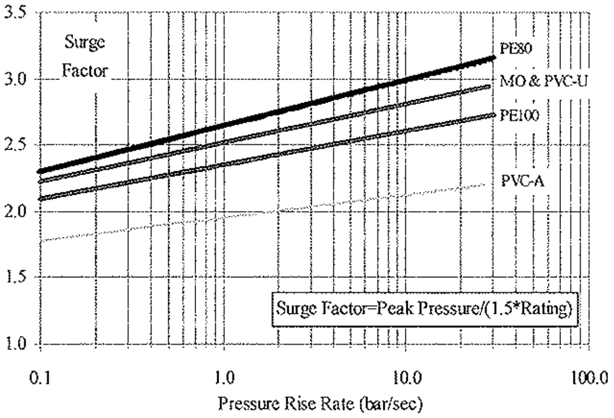
Surge design

There are random, isolated events in which pressures may surge to high levels without causing fatigue problems (e.g. emergency pump shutdowns). For such cases, it is necessary to specify the allowable pressure limits for each material to resist these peak surge events. It should also be noted that a value for maximum pressure resistance including surge will be an EN requirement when prEN805 is ratified.

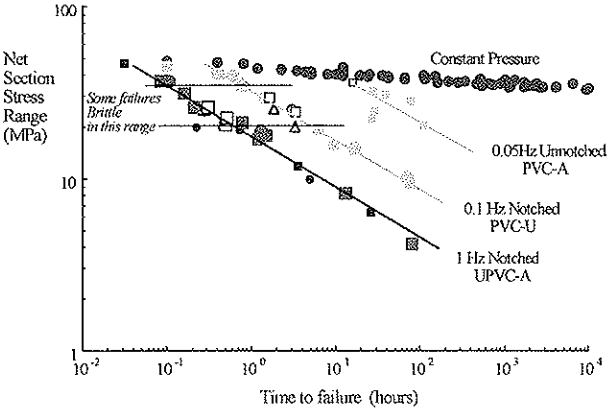
It is the responsibility of the system designer to choose whether to conduct a formal surge analysis, although this is recommended whenever the slightest doubt about operating conditions exist. For all rising mains, trunk mains, and special pump/valve circumstances a detailed surge analysis should be conducted. For the identification of the peak surge, the worst anticipated event (e.g. emergency trip of all pumps) should be considered.

As part of a previous water industry and BPF research programme,[2] it has been determined from detailed inspection of historical designs and field measurements that for PE pipes in distribution systems, no surge event showed increase rates of more than 8 bar s^{-1}. To determine the allowable pressure resistance of thermoplastic pipes, it is possible to use data relating pressure resistance to the rate of pressure increase (Fig. 2) to compute 'surge factors'.

The peak pressures at all rates were divided by a safety factor of 1·5 and then by the pressure rating to produce the graph shown in Fig. 3. The lines shown can be used to determine the appropriate pressure class. The evidence for the testing shows that standard thermoplastics used by the UK water industry will sustain pressures in excess of twice their static ratings



3 **Surge factors for range of thermoplastics pressure pipes**



4 **Comparison of data on uPVC with modified PVC-A; notched uPVC-A gave same life; some brittle failures occurred at 20–30 MPa**

at high rates of pressure increase. It should be noted that if the designer increases the wall section to gain a greater safety factor, then the surge analysis should be repeated, since the surge calculation itself is dependent on the standard dimensional ratio (SDR; pipe outer diameter/wall thickness). Stiffer pipes will cause higher wave speeds and peak values to be generated.

Fatigue

There is considerable information in the literature regarding the determination of the properties of uPVC materials under cyclic loading.[3–15] There are reports on tests made to determine the strength variation using unnotched pipes and sample pieces and other studies on pre-notched samples in which crack growth characteristics have been measured. There has been investigation of a wide range of different types of PVC, including data obtained on molecular oriented (MO) PVC.

On the other hand, there is little reported work on the range of new 'second generation' medium density polyethylene (MDPE) PE80 and 'third generation' high density polyethylene (HDPE) PE100 materials, which are used by the water industry. The range of polymers that have been studied mostly includes first generation MDPE[16,17] and low toughness HDPE materials.[18] To rectify this situation and to provide a rational basis for the review of the UK design methodology, which is appropriate at the present time, a detailed experimental programme has been carried out by Pipeline Developments Ltd on behalf of UK Water Research Ltd to study the high toughness PE and PVC materials that are currently being installed in the UK.

PVC FATIGUE TESTING

Effect of *R* ratio

In practice, pipes are frequently subjected to pressure cycles in which the lower bound is a positive pressure. The ratio of minimum stress/maximum stress imposed during cyclic loading is known as the *R* ratio and hence gives a measure of the effect of variations in mean stress at a given maximum stress.

Tests on PVC materials loaded via three point bending on notched samples, for which the defect was 25% of the wall section, were determined as stress range *v.* time to failure. The results show that for *R* ratios between 0·1 and 0·5 there is very little difference in lifetimes. From all the tests conducted it was determined that the stress range and not the simple peak stress was the primary controlling parameter in the control of failure time/cycles. Stress range was therefore used for comparing fatigue data from different sources, particularly at low *R* ratios.

Effect of waveform

When testing in single edge notched tension or three point bending, different cyclic waveforms such as sine, square, and saw can be imposed on the testpiece. Data obtained at 0·1 Hz for uPVC have shown no significant difference in lifetimes when different waveforms were used.

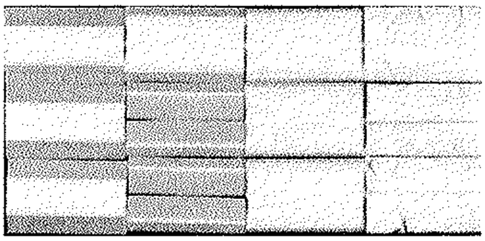
Effect of type of PVC

Data obtained at 1 Hz (Fig. 4) show that samples of similar thickness of both uPVC and PVC-A, modified with chlorinated polyethylene (CPE), give very similar lifetimes in notched sample tests.

Failure modes

In general, it has been found that there is little evidence of true brittle growth on the fracture surfaces of the notched three point bending specimens. The fracture surfaces almost always display the extensive stress whitening normally associated with ductility, apart from tests in the stress range 20–30 MPa, for which random brittle failures were observed in tests on both uPVC and the CPE modified material. There was no noticeable change in the slope of the data where this transition occurs and the switch in mode appears to be independent of the frequency of loading. For stress ranges above 30 MPa and at stresses below 20 MPa, the failure mode was always ductile. Figure 5 shows ductile and brittle failure modes in PVC-A samples.

A series of notch depth tests were undertaken on PVC-A three point bending samples at a stress range of 25 MPa. It was found that samples with notches extending to 25% of the pipe wall section gave the lowest failure times. The random brittle failures were only observed in samples with this notch/depth ratio. This can be expected, since cracks at 25% of the



5 Ductile and brittle failure modes in PVC-A samples

depth represent the most severe case for ductile–brittle transitions.

Stress *v.* cycles to failure characteristics for PVC

A summary of the stress *v.* cycles to failure graph for different types of PVC is shown in Fig. 6. All the data on unnotched samples of PVC tested as part of the present programme are combined with data obtained in other programmes, including MOPVC.[10]

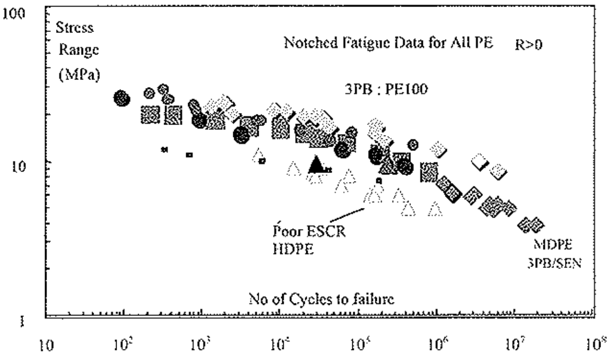
The most notable feature of this stress *v.* cycles to failure curve is that there is excellent consistency of the data for both PVC-A and uPVC. All types of PVC (other than MOPVC) apparently have identical fatigue characteristics. This is also true for the studies using pre-notched samples.

That data for PVC of high and low static toughness agree so closely and that there is apparently no difference between materials produced in a wide range of different countries is very unusual. This does not explain why the service problems with uPVC pipes were largely confined to pipe used in the UK and different suppliers had very different failure rates. If fatigue had been responsible for poor service performance on pumped sewer and water mains, and given that all PVCs have poor fatigue characteristics, then it would be expected that the whole of the US plastic system would have been experiencing major problems. The USA has used far more PVC pipes in pumping applications than the UK and yet they have virtually no history of failures.

FATIGUE TESTING OF PE PIPE MATERIALS

Cyclic loading of PE80 (MDPE)

Tests were carried out on single edge notch samples loaded in tension. These tests produced failures at much reduced times owing to gross bulk heating of the samples. Temperature increases of up to 25°C were measured. As such increases are not expected in service because of the heat sink effect of the water conveyed, testing in this configuration was abandoned.



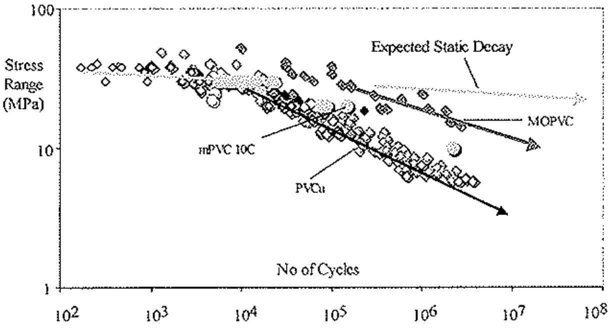
7 Notched samples stress *v.* cycles to failure graph for all PEs

When the MDPE data were plotted as stress against cycles to failure, as in Fig. 7, it can be seen that there is consistency between the different test methods for the MDPE material. However earlier tests by Batelle Columbus Laboratories[16] using pipe with socket and butt welded joints tested in rotating bending gave reduced lifetimes. It is believed that these tests were conducted using a grade of MDPE with inferior slow crack growth resistance characteristics.

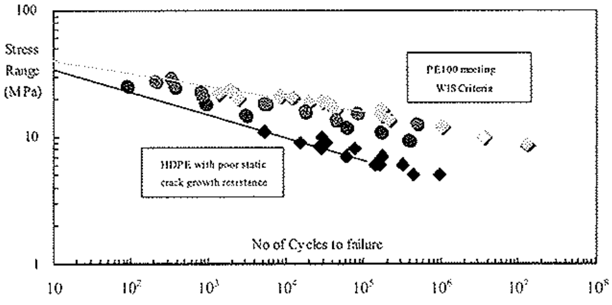
Cyclic loading of PE100 (HDPE)

Figure 8 shows three point bending data obtained for HDPE at 0·5 Hz. Good agreement is reached between data obtained in the present programme with that obtained at BP Chemicals, without evidence of a dramatic knee in the data. The present tests were conducted under different loading waveforms, which showed no difference in lifetime. Deeper samples produced from thicker sheet gave a marginal decrease in lifetime. As for the MDPE samples, only ductile failures were observed.

Unlike PVC, both MDPE and HDPE materials appear to have fatigue characteristics that are sensitive to the grade of polymer used. Those polymers with exceptional long term static crack growth resistance have excellent 'fatigue' properties. Those polymers with poor stress crack resistance will fail prematurely in fatigue.



6 Regression of strength of PVC materials under cyclic loading



8 Regression of strength of PE materials under cyclic loading

Long term PE fatigue performance

The PE fatigue data show many similar features to PVC in that knees on the static stress regression line were observed for some of the PE materials tested. However the change in slope occurs at longer times than that for PVC and it is not as steep. The effect of different variables is more difficult to determine for PE since longer testing times are required. Sufficient data was collected however, to determine that waveform, test method, sample depth, and frequency have little or no effect on the number of cycles to failure. Temperature increases of 5 K in three point bending and 20 K in single edge notch tension, combined with failure in the ductile mode suggest that a temperature controlled yielding mechanism may be responsible for ultimate failure.

There is no evidence either from laboratory testing or service experience to suggest that fatigue represents a significant practical problem. Following much debate within the UK, it has been decided that the decision to derate PE materials, which have excellent static stress crack resistance, was unjustified.

DESIGN ADVICE FOR THE UK WATER INDUSTRY

Operation at ambient temperature

A major meeting, involving all prominent researchers in the field, pipe manufacturers, material suppliers, and the water companies, was held to discuss the findings of the UK Water Industry Research Ltd programme and agree on new advice for water and sewerage applications. The following recommendations were agreed.

1. Surge and fatigue are two distinctly different loading conditions and can thus be treated separately.
2. The evidence for a true fatigue phenomenon having caused historic problems with PVC is not strong. However, the existing data, which demonstrate dramatic 'knees', cannot be ignored.
3. The main controlling fatigue variable is stress range, therefore design should be undertaken by comparing this envelope with the number of cycles to failure, and then designing against the number of real events likely to be encountered.
4. Derating can be undertaken by use of power law fits to average lines through available data giving derating factors; MOPVC has greater fatigue resistance and hence higher factors.
5. There is no evidence of fatigue in PE80 and PE100 materials, which meet UK Water Industry Specification (WIS) criteria for stress crack resistance, and therefore no derating is required. However, as with the other materials, these PEs would still be expected to cope with over pressurisation due to surge.
6. Other PE materials, for which there is no data to satisfy WIS specifications, give cause for concern. These may have poor stress cracking resistance and hence display reduced fatigue lifetime. For such polymers, derating should be carried out in accordance with a power law fit of the lower bound of the data on the low toughness HDPE.

Given these criteria, derating factors for fatigue have been calculated using power law fits to the fatigue data (following practice now being adopted in Australasia) and these are shown in Table 1. The following should be noted.

1. For all PVC based materials, there should be derating to allow for the decrease in strength as a function of repeated cyclic loading.
2. The predicted stress range should be multiplied by the factors tabulated below to give the pipe rating required to safeguard against fatigue.
3. When considering fatigue, the range used should be that for the frequently repeated events (e.g. pump start/stop) and the frequency and total number should relate to all events (pump starts and stops).
4. The extreme emergency case of total pump shutdown should not be a repeated event and only needs to be considered in the surge design to ensure that extreme high and low pressures are considered.

It is recommended that the pressure rating of selected pipe must always be greater than the maximum steady state pressure.

Effect of temperature

A recent study[19] has shown that altering the test/service temperature can significantly alter the lifetime of PVC-A pipes. Reducing temperature from 30 to 5°C gives an order of magnitude increase in lifetime. The lifetimes of uPVC are changed in the same way, but to a significantly lower degree.

In clean water systems, the average water temperature in a buried uPVC pipe in the north of England (measured over a two year period) has been found to be 11°C.[20] At higher temperatures, there is a reduction in lifetime for PVC materials and for pumped sewerage mains it may be appropriate to consider average operation at a higher than ambient temperature.

The coefficients that should be used to multiply the 20°C rerating factors given in Table 1 are presented for a range of temperatures in Table 2.

Table 1 Recommended fatigue rerating factors for plastics materials

			Rating factor			
Daily frequency	Hourly frequency	Total cycles in 50 years	PVC-A and uPVC	MOPVC	MDPE and HDPE (not tested to WIS)	High toughness PE80 and PE100 (tested to WIS)
4	0·2	73 000	0·7	0·6	1·1	0·5
24	1·0	438 000	1·3	0·9	1·5	0·5
48	2·0	876 000	1·5	1·1	1·7	0·5
120	5·0	2 190 000	2·0	1·3	2·0	0·5
240	10·0	4 380 000	2·5	1·5	2·3	0·5
1200	50·0	22 000 000	4·0	2·0	3·0	0·5

Table 2 Coefficients to multiply rerating factors given in Table 1 to account for temperature

Temp., °C	PVC-A	uPVC
5	0·67	0·89
10	0·72	0·91
15	0·85	0·97
20	1·0	1·0
25	1·14	1·03
30	1·3	1·07

It is a matter for the design engineer's judgement to decide the operating temperature. If temperatures below 20°C are appropriate, multiplying by the coefficients gives lower derating factors and *vice versa* for temperatures above 20°C. It should be noted that for MOPVC and PE materials, the allowable stress rating is recommended to be adjusted by 1·3% for every 1°C in excess of 20°C, to account for a simple loss in static strength.

CONCLUSIONS

The work outlined in the present paper and the associated advice on rating factors to cope with both surge and fatigue, is to form the basis of a new Information and Guidance note (WIS 4-32-07), to be issued by the water industry's trade association (Water UK), as the standing advice on pressure pipe design for plastics systems. The WIS will be issued in 1999.

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