Evaluation of the Surge and Fatigue Resistance of PVC and PE Pipeline Materials for use in the U.K. Water Industry

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1. INTRODUCTION

Many early brittle failures in 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 (ref. 1) by the UK water industry, 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 shut down 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 time-scale and it is known that many PVCu 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-pressurization from surge and loss in properties caused by fatigue could have serious implications on the lifetimes of PVCu pipelines, a design code was introduced in 1977 (BS CP312). The advice for design from both CP312 and the PMSM is that in a dynamic loading situation, the difference between maximum and minimum pressures must be less than 0.5*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 rise to twice the steady state condition and drop 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 PVCu in the PVC Guidance Manual and the Water Research Centre (WRc) extended the range of materials affected to include PE pipe materials in the Pipe Materials Selection Manual (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 PVCu were associated with static overloading rather than fatigue, clarification of the U.K. 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. (UKWIR) to define the position for the range of tough polymers currently in use in the UK Water Industry.

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1.1 Defining Surge

In a pumped system, the most frequent events that cause unsteady variations in pressure are pump start-up 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 (ref. 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 25mm PE pipe is shown in Figure 1. For larger distribution and branch mains, the rise 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 sub-atmospheric. Many engineers fear that extremes of both high and low pressure may cause damage and that high-pressure peaks may cause pipe rupture.

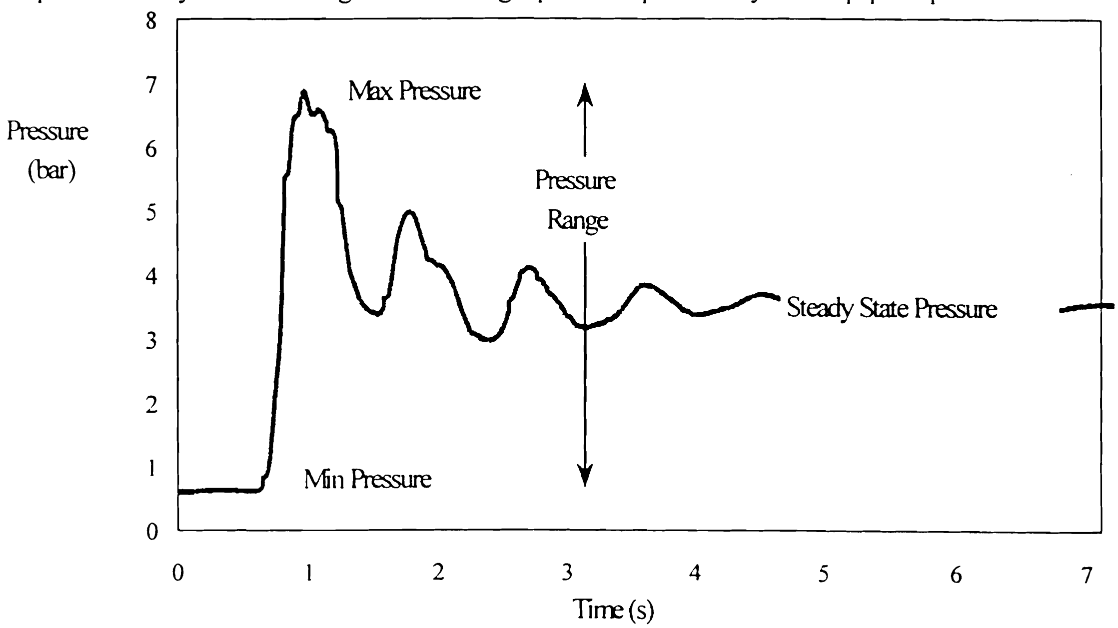

Figure 1: Typical Pressure Fluctuation from Sudden Valve Closure in a PE SDR11 Pipe

It should be noted that the stiffnesses of plastic pipes are lower than for metal/AC pipes and thus the pressure shock wave transmission speeds are lower. Hence, the pressure rise 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.

1.1.1 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 materials' entangled molecular structure provides resistance to deformation. At high pressurisation rates pipes are better able to resist the higher stress levels generated by surge. Also, the strength of both materials will increase with high rates of loading.

Tests have been made on various PVC and PE pipes where the pressure was raised at different rates until failure occurred. All the pipes were prepared by machining 100mm 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 Figure 2 where pressures at failure for PVC and PE pipes of different static pressure ratings are given as a function of loading rate.

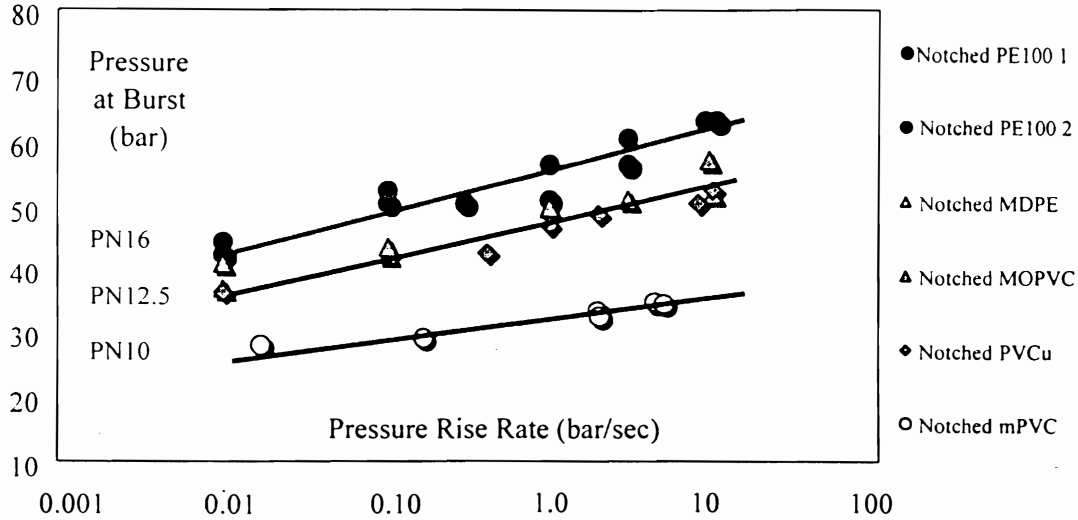

Figure 2: Effect of Pressure Rise Rate on Strength of Plastics Pipes

The burst test data show that, at pressure rise rates typically occurring in surge events (0.1 – 10bar/sec), all PVC and PE pipes have strengths well in excess of their respective static stress ratings. Thus, for these materials, the swift rise in pressure that is the characteristic of surge is not necessarily a significant practical problem.

1.1.2 Surge Design

There are random, isolated events where pressures may surge to high levels without causing fatigue problems (e.g. emergency pump shut downs). 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 though this is recommended wherever 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 (ref.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 rise rates of more than 8bar/sec.

To determine the allowable pressure resistance of thermoplastic pipes, it is possible to use data relating pressure resistance to the rate of pressure rise (Figure 2) to compute 'surge factors'.

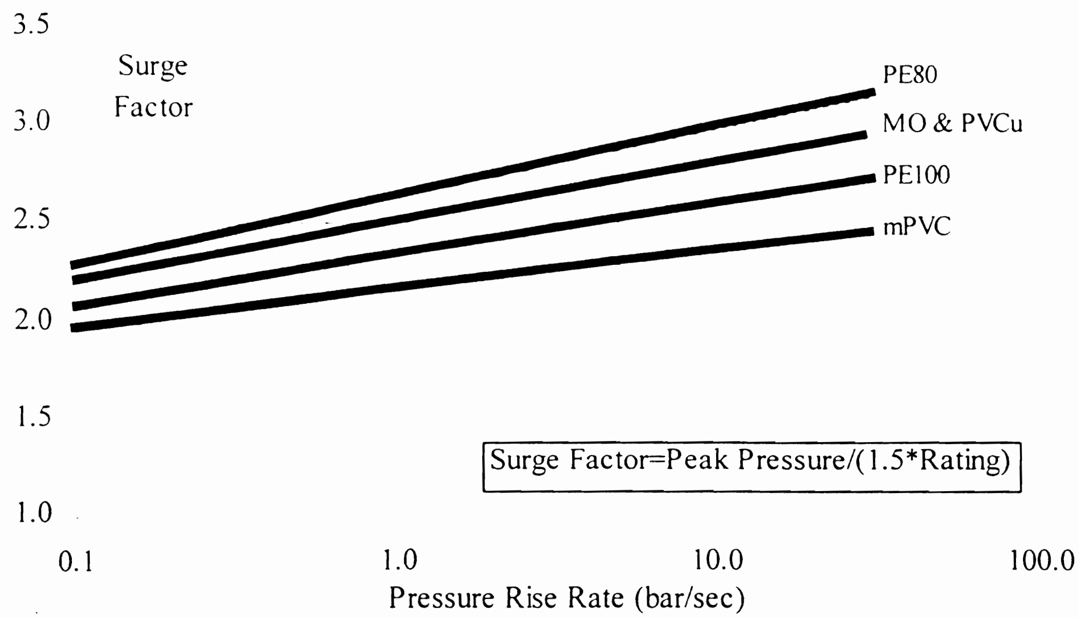

Figure 3: Surge Factors for a Range of Thermoplastics Pressure Pipes

The peak pressures at all rates have been divided by a safety factor of 1.5 and then by the pressure rating to produce the graph shown in Figure 3. The lines shown may be used to determine the appropriate pressure class. The evidence from the testing shows that standard thermoplastics used by the U.K. Water Industry will sustain pressures in excess of twice their static ratings at high rates of pressure rise. 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 dependant on the SDR which is used. Stiffer pipes will cause higher wave speeds and peak values to be generated.

1.2 Fatigue

There is a large body of information in the literature regarding the determination of the properties of PVCu materials under cyclic loading (refs. 3-13,17-18). There are reports on tests made to determine the strength variation using unnotched pipes and sample pieces and other studies on pre-notched samples where crack growth characteristics have been measured. There has been investigation of a wide range of different types of PVC-including data obtained on MOPVC.

On the other hand, there is little reported work on the range of new PE80 and PE100 materials which are used by the Water Industry. The range of polymers which have been studied mostly includes first generation MDPE (refs. 14,15) and low toughness HDPE materials (ref. 16).

To rectify this situation and to provide a rational basis for the review of the U.K. design methodology which is appropriate at the present time, a detailed experimental programme has been carried out by PDL on behalf of U.K. Water Research Ltd. to study the high toughness PE and PVC materials which are now being installed in the U.K.

2. PVC FATIGUE TESTING

2.1 Effect of R Ratio

In practice, pipes will frequently be subjected to pressure cycles where the lower bound is a positive pressure. The ratio of minimum stress to 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 (3PB) on notched samples where the defect was 25% of the wall section have been determined as stress range versus time to failure. The results have shown that for R ratios of 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 has therefore been used for comparing fatigue data from different sources-particularly at low R ratios.

2.2 Effect of Waveform

When testing in single edge notched tension (SEN) or 3PB different cyclic waveforms such as sine, square and saw can be imposed on the test piece. Data obtained at 0.1Hz for PVCu have shown no significant difference in lifetimes when different waveforms were employed.

2.3 Effect of Type of PVC

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

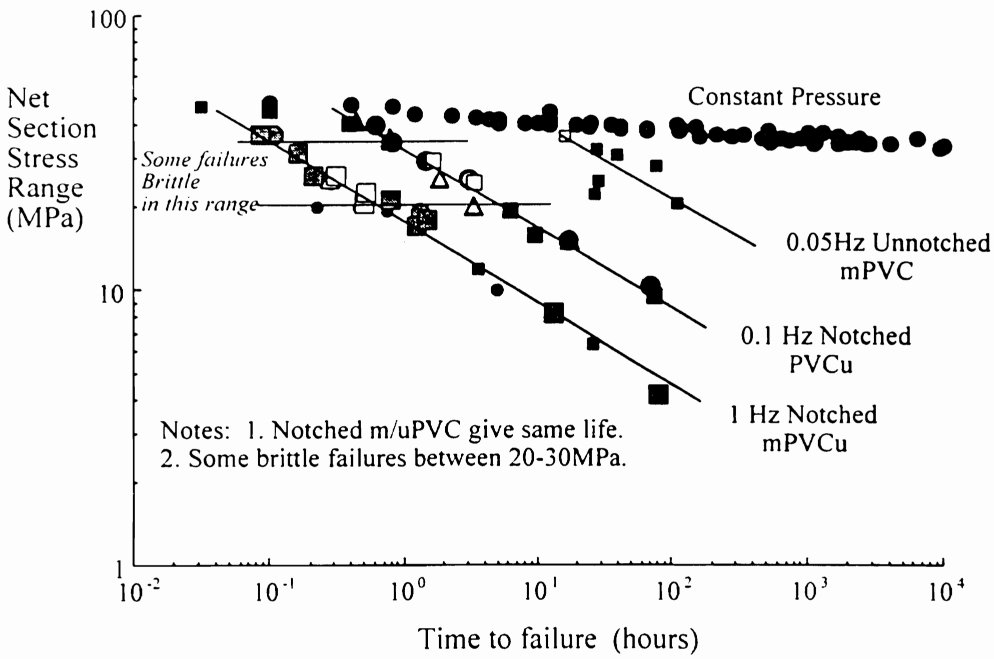

Figure 4: Comparison of data on PVCu and modified PVC

2.4 Failure Modes

In general, it has been found that there is little evidence of true brittle growth on the fracture surfaces of the notched 3PB specimens. The fracture surfaces almost always display the extensive stress whitening normally associated with ductility-apart from tests in the stress range of 20 to 30MPa where random brittle failures were observed in tests on both PVCu and 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 30MPa and at stresses below 20MPa, the failure mode was always ductile.

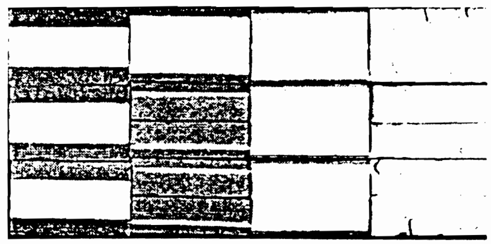

Figure 5: Ductile and Brittle Failure Modes in mPVC Samples

A series of notch depth tests were undertaken on mPVC 3PB samples at a stress range of 25MPa. 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 is not unexpected, since cracks at 25% of the depth represent the most severe case for ductile/brittle transitions.

2.5 Stress vs Cycles to Failure Characteristics for PVC

A summary stress/cycles to failure graph for different types of PVC is shown in figure 6. All the data on unnotched samples of PVC tested here, are combined with data obtained in other programmes, including oriented PVC (ref 10).

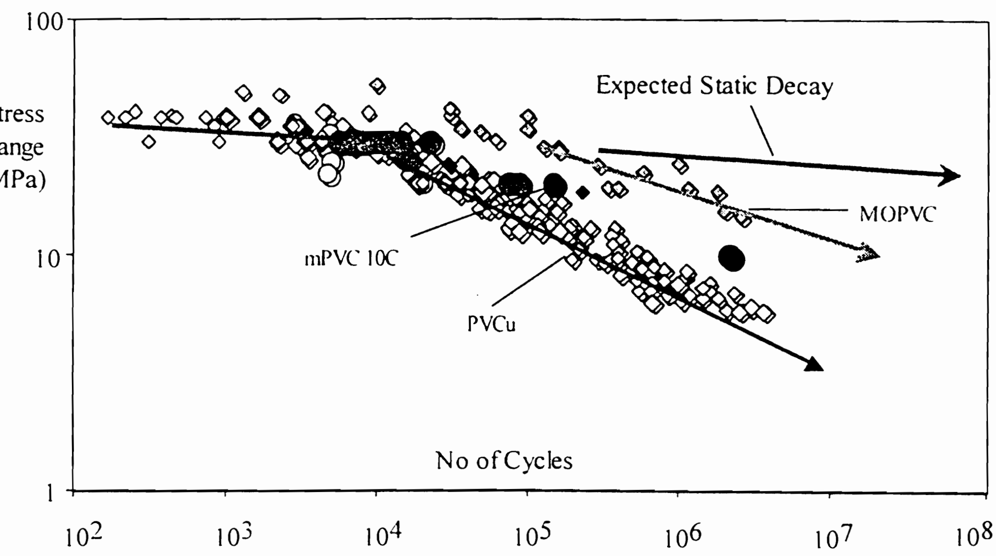

Figure 6: Regression of Strength of PVC Materials under Cyclic Loading

The most notable feature of this S/N curve is that there is quite excellent consistency of the data for both mPVC and PVCu. 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 odd. This does not explain why the service problems with PVCu pipes were largely confined to pipe used in the U.K. 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 US has used far more PVC pipes in pumping applications than in the U.K. and yet they have had virtually no history of failures.

3. FATIGUE TESTING OF POLYETHYLENE PIPE MATERIALS

3.1 Cyclic Loading of PE80 (MDPE)

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

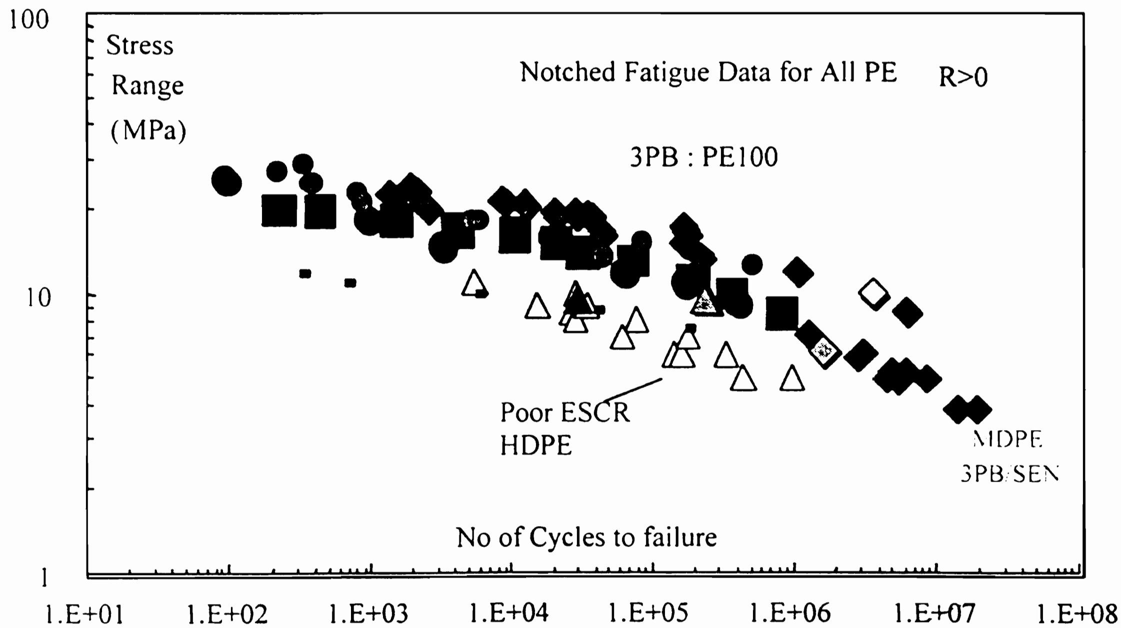

Figure 7: Notched Samples S/N Graph for All PEs

When the MDPE data were plotted as stress against cycles to failure, as in figure 7, it can be seen that there is consistency between the different test methods for the MDPE material. However earlier tests by Batelle (ref. 14) using pipe with socket and butt-welded joints tested in rotating bending gave reduced lifetimes. It is believed that the these tests were conducted using a grade of MDPE with inferior slow crack growth resistance characteristics.

3.2 Cyclic Loading of PE100 - HDPE

Figure 8 shows 3PB data obtained for HDPE in 3PB at 0.5Hz. Good agreement is reached between data obtained at PDL and that obtained at BP, without evidence of a dramatic knee in the data. The PDL tests were conducted under different loading waveforms, which showed no difference in lifetime. Deeper samples produced from thicker sheet were seen to give a marginal decrease in lifetime. As with the MDPE samples only ductile failures were observed.

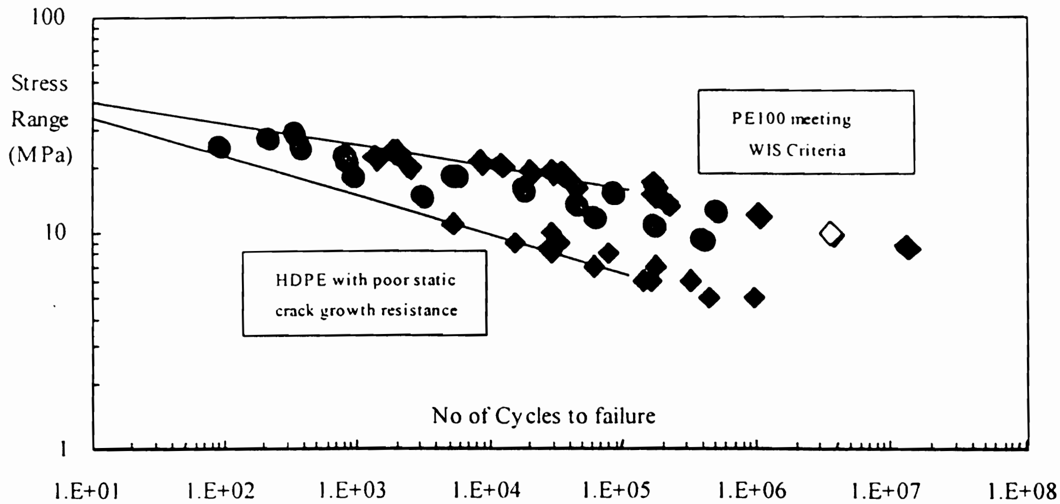

Figure 8: Regression of Strength of PE Materials under Cyclic Loading

It would seem that, unlike PVC, both MDPE and HDPE materials have fatigue characteristics, which are sensitive to the grade of polymer which is 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.

3.3 Long Term PE Fatigue Performance

The PE fatigue data show many similar features to PVC in that knees on the static stress regression line have been observed for some of the PE materials tested. However the change in slope occurs at longer times to 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 has however been collected in order to determine that waveform, test method, sample depth and frequency have little or no effect on the number of cycles to failure.

Evidence of temperature rises, combined with failure in a ductile mode suggests that a temperature controlled yielding mechanism may be responsible for ultimate failure.

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

4. DESIGN ADVICE FOR THE U.K. WATER INDUSTRY

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 UKWIR research 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 variables are stress range and number of cycles to failure, so design should be undertaken on this basis.

4. De-rating can be undertaken by use of power law fits to average lines through available data giving de-rating 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 de-rating 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, where 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, de-rating 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, de-rating 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.

			mPVC & PVCu	MOPVC	MDPE HDPE	High (-Hi) Toughness PE80, PE100
					Not tested to WIS	Tested to WIS
Daily Frequency	Hourly Frequency	Total Cycles in 50 years	Rating Factor	Rating Factor	Rating Factor	Rating Factor
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 1: Recommended Fatigue Re-rating Factors for Plastics Materials

It should be noted that:

1. For all PVC based materials, there should be de-rating 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 above 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.

The work outlined here, 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, to be issued by the Water Industry's trade association (Water U.K.), as the standing advice on pressure pipe design for plastics systems. The IGN will be issued in 1998.

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