RESISTANCE OF PVC-U AND PVC-M TO CYCLIC FATIGUE

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ABSTRACT

PVC-U and PVC-M pipes may be used in applications where they are subjected to cyclic pressures generated by the operation of pumps and valves. It is therefore important that the pipe material's response to cyclic loading is quantified and that pipelines are designed and operated within the material's established capability. Using rotational bending specimens, PVC-U and PVC-M were shown to exhibit very similar resistance to crack growth under cyclic loading. That is, the increased static toughness of PVC-M did not manifest itself in an increased resistance to fatigue crack growth rate. It was further shown that PVC-U and PVC-M exhibit similar increase in fatigue crack growth rate as the test temperature increased. The rotational bending method was also used to investigate the fatigue threshold of PVC-M and PVC-U. Both materials were found to exhibit a threshold stress intensity factor, ΔK_{th}, of approximately 0.3 MPa.m$^{0.5}$ at 20°C. It is concluded that the same cyclic fatigue design principles should be applied to both PVC-U and PVC-M pipes. Moreover, the existence of a threshold value should be taken into account so that derating for fatigue is not required if the amplitude of the stress intensity factor is below the threshold.

INTRODUCTION

Poly (vinyl chloride) (PVC), like many other materials including polymers, is subject to cyclic fatigue (1). That is, it can fail at lower stresses when subjected to cyclic loading than when a static load is applied. Gotham (2) introduced the concept that PVC behaves as if it has two reserves of fatigue resistance, one static and the other dynamic. This means that a pipe exhibits a similar resistance to cyclic loading irrespective of whether it has been subjected to a prior static load. Thus, the cyclic fatigue performance can be dealt with in isolation.

A number of premature failures were experienced in PVC pressure pipes in the U.K. in the 1970s (3). These failures were attributed to inadequate design against cyclic loading in conjunction with poor installation, inappropriate pressure class, badly designed pressure control devices and in some cases, poor quality pipe. Subsequent changes to the British Code of Practice (4) restricted the use of lower pressure classes in cyclic applications and imposed some design guidelines. For example, the maximum surge pressure was restricted to the rated working pressure of the pipe and the pressure amplitude limited to half of the rated working pressure of the pipe. Working in The Netherlands, Stapel (5, 6), proposed a similar set of restrictions for cyclic loading of PVC-U pressure pipes.

To what extent dynamic fatigue was the cause of premature failures in the U. K. has been the topic of debate. Brogden (7), Marshall (8) and Kirby (9) have all acknowledged the contribution to premature failure to low toughness PVC and point loads due to poor installation. The subsequent improved performance of PVC pressure pipe has been attributed to the adoption of a fracture toughness test and better control of installation conditions.

Nevertheless, PVC pipes may be used in situations where they are subjected to cyclic loading and consideration has to be given to their fatigue behaviour.

Joseph (10) examined the published data relating to the fatigue testing of PVC-U pipes, plotting stress amplitude versus cycles to failure. He established a lower bound, defined by equation (1). Joseph and Leevers (11) subsequently tested a large number of pipe samples and confirmed the appropriateness of the lower bound [Fig. 1]. Joseph's lower bound was incorporated into the design principle (12) adopted in Australia in 1997 [Fig. 2]. In order to normalise the data so that it is applicable to all pressure classes, the Australian design practice is presented in the form of a fatigue load factor (FLF), (i.e. pressure amplitude divided by rated working pressure of the pipe) versus cycles to failure.

$$\Delta\sigma = \frac{352}{N^{\log 2}} \qquad (1)$$

where $\Delta\sigma$ is the stress amplitude and N the number of cycles to failure.

For reasons of economy, test duration and the durability of test equipment, cyclic pressure testing of pipes has generally been performed at higher amplitudes and hence shorter failure times. In order to accommodate lower pressure amplitude cycles, the Australian design practice includes an extrapolation of Joseph's lower bound, with little regard as to whether fatigue failures continue to occur irrespective of how small the pressure amplitude is. The design practice implies that, irrespective of how small a pressure wave is, fatigue failure will ultimately occur. Truss (13) developed a failure model based on fracture mechanics and which included a fatigue threshold, but this has not been widely adopted. Truss's threshold equated to a pressure amplitude of just a little lower than half the rated working pressure of the pipe. In the present work, particular emphasis has been placed on the performance of PVC under conditions of low stress amplitude, that is, the threshold region.

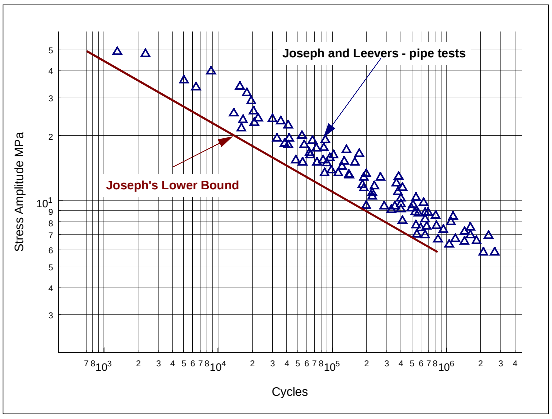

Figure 1. Joseph's lower bound together with fatigue results of Joseph and Leevers (11).

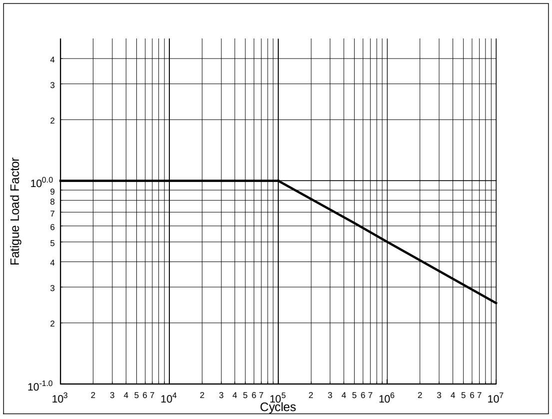

Figure 2. Design against dynamic loads for PVC-U as published by PACIA (12).

When PVC-M pressure pipes were introduced in Australia on the late 1990s, it was accepted the fatigue behaviour of the material was similar to PVC-U. However, because PVC-M pipes operate at a higher stress, the design against dynamic fatigue shifted to a smaller number of cycles for a given fatigue load factor [Fig. 3]. In neither case was any provision made for pressure excursions to exceed the rated working pressure of the pipe. In contrast, the fatigue derating models adopted by the U.K. water industry (14) are less conservative, being based on the line of best-fit of Joseph and Leevers' data, rather than a lower -bound and also permitting "over-pressurisation" of PVC-U [Fig. 4]. Note that Australian PVC-U and PVC-M pipe materials have been shown to have similar crack growth rates under cyclic loading using compact tension specimens (15). Note also that the product called PVC-M in Australasia is known as PVC-A in the U.K.

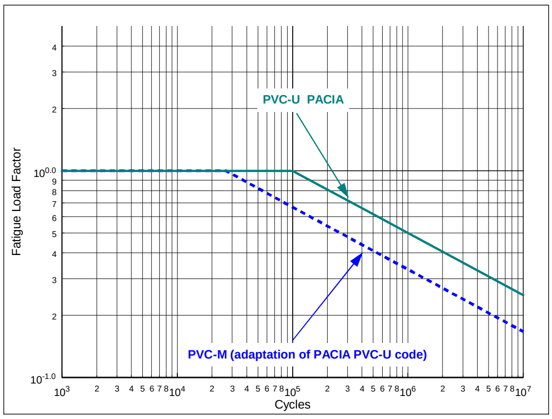

Figure 3. Australian model for design against fatigue - PVC-U according to PACIA, plus adaptation for PVC-M.

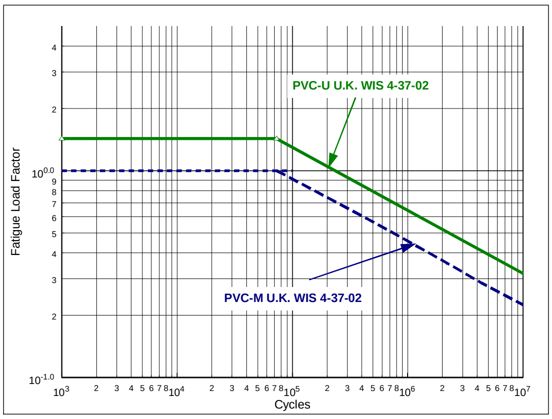

Figure 4. U.K. WIS 4 –37 – 02 design against fatigue expressed in terms of the Australian FLF.

Lawrence et al (16) reported that PVC-M and PVC-U did not share the same cyclic fatigue versus temperature relationship. PVC-M apparently having a greater sensitivity to changes in temperature, performing better than PVC-U at < 20°C but worse at > 20°C. As part of this work, the temperature dependency of the cyclic fatigue resistance for both PVC-U and PVC-M has been investigated.

Brogden (7) demonstrated comparable results are obtained for both 3 point bend tests and rotational bending tests performed at the same frequency, provided that only the tensile component of the stress range is considered with the latter configuration. That is, the compressive component of the rotational bending cycle had no significant effect upon the fatigue life. Rotational bending was chosen for this work because of the simplicity of the method and equipment and because it allowed a lot of data to be generated more quickly than many other methods. A disadvantage of the method is that whilst the initial stress amplitude and stress intensity factor amplitude are known, the progressive rate of crack growth is not directly measurable.

By way of comparison, Brogden's rotational bending results on notched rods are plotted together with Joseph and Leevers' un-notched pipe test results [Fig. 5]. At the same stress amplitude, the rods failed well before the pipes.

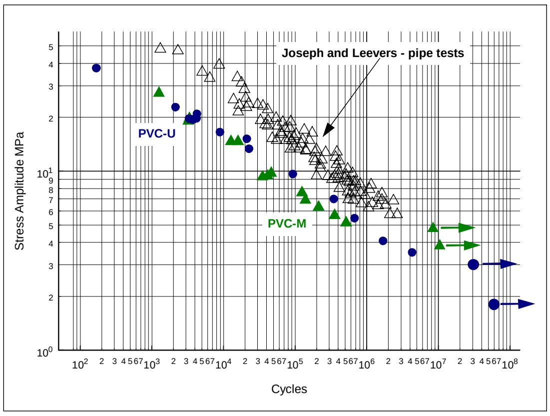

Figure 5. Brogden’s results (PVC-U and PVC-A) compared to Joseph and Leevers’ pipe tests.

MATERIALS

PVC-U and PVC-M Series 2 pipes (CIOD) were extruded on a commercial, twin-screw extruder to the requirements of Australian / New Zealand Standards AS/ NZS1477 and AS/NZS4765 respectively. The pipes were made from a PVC resin with a *K* value of 67 and contained a calcium-zinc thermal stabiliser. The formulations also contained 1.5 parts per hundred resin by mass (pphr) of rutile titanium dioxide in accordance with Australasian requirements plus a small amount of ground, coated whiting. The PVC-M formulation also contained 6 pphr of chlorinated polyethylene in the manner described by Holloway and Naakgeboren (17).

EXPERIMENTAL

Sections of pipe were heated to 120°C in an air-circulating oven, flattened in a hydraulic press and cooled slowly to room temperature. Circular rods, 130 mm long and 10 mm in diameter were turned on a lathe from the flat sheets. A sharp, circumferential notch was cut in each rod ~ 90 mm from one end, such that the remaining ligament was 7.5 mm diameter. The orientation of the rods was such that their length coincided with the original hoop direction of the pipe. Thus the direction of crack growth through the ligament was consistent with the longitudinal axis of the pipe. The rods were mounted in turn in a purpose-built apparatus fitted with a variable speed motor and subjected to a bending moment [Fig. 6]. The number of cycles to failure was noted or alternatively, the test was discontinued if failure did not occur at > 3,000,000 cycles. When required, the amplitude of the initial stress intensity factor, ΔK_I, was calculated from the dimensions and applied bending moment, *M*, using equation 2 (18).

$$\Delta K_I = \frac{4M}{\pi a^3}\sqrt{\pi a}\,F_1\left(a/b\right) \tag{2}$$

where *2a* is the diameter of the ligament and *2b* the diameter of the rod.

A small electric fan directed a stream of air over the ligament in order to maintain a constant temperature. Adequate control of the temperature at the notch was confirmed using an infrared pyrometer. The first series of tests were performed at 3 Hz. Subsequent tests were performed at 19.3 – 19.8 Hz in order to accumulate results more quickly, especially in the threshold region.

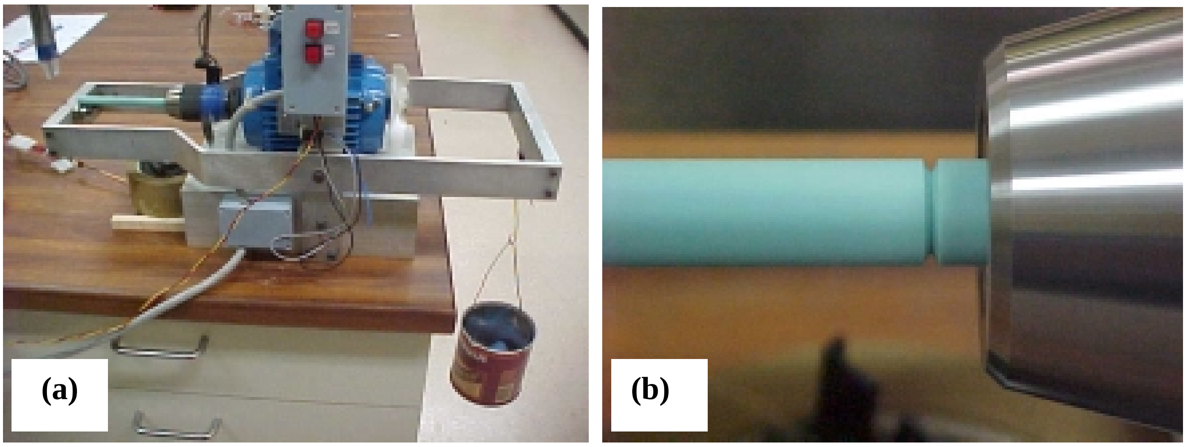

Figure 6. Rotational bending apparatus (a) and specimen with notch (b).

To verify the robustness of the method, some rods of both PVC-M and PVC-U were turned and notched at Iplex Pipelines and fatigue tested at Pipeline Development Limited in the U.K, using a similar apparatus. A parallel set of rods, also turned at Iplex, was notched at Pipeline Development Limited and tested at Iplex. Both sets of results were compared with those obtained on rods completely prepared and tested at Iplex.

To assess the temperature sensitivity of the fatigue resistance, the rotational bending apparatus was placed in an air-circulating oven and further sets of rods tested at temperatures of 30°C and 40°C.

Finally, to confirm that specimens tested to beyond 3,000,000 cycles without failure were in fact below the threshold, some were retested at a higher stress. The results were assessed to determine whether they were consistent with the results for specimens that had not been previously stressed.

RESULTS AND DISCUSSION

The results of rotational bending tests performed at 3 Hz and 20°C confirm the two pipe materials, PVC-M and PVC-U, exhibit a similar resistance to cyclic fatigue [Fig. 7]. It can also be seen that the results for specimens notched at PDL and tested at Iplex and those notched at Iplex and tested at PDL are indistinguishable from those both notched and tested at Iplex. The method therefore appears to be robust. However, it was noted the fatigue resistance of both the PVC-U and PVC-M pipe materials exceeded the performance reported by Brogden (7) for U.K. manufactured PVC-U and PVC-A [Fig. 8]. Brogden noted the PVC-U pipe used in his work was extruded in the 1970s, suffered heavy attack in methylene chloride and had a low fracture toughness. Notwithstanding the observation of Mai and Kerr (19) that fatigue resistance is largely independent of gelation, the quality of the U.K. PVC-U may have contributed to the poor fatigue resistance. On the other hand, the PVC-A pipe was made in the 1990s, had a good level of processing yet still had poorer resistance to fatigue than the PVC-M. Details of any differences in composition are not known except that the products tested in this work were Ca-Zn stabilised whilst the U.K. pipes are understood to be lead stabilised.

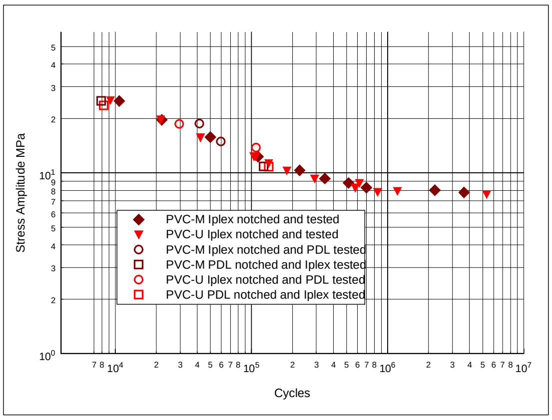

Figure 7. Initial tensile bending stress versus cycles-to-failure for Iplex PVC-U and PVC-M, including inter-laboratory testing.

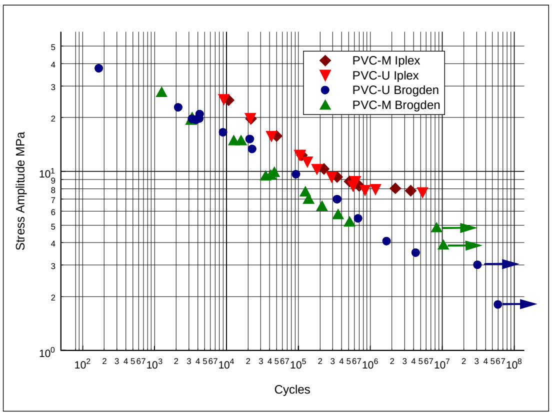

Figure 8. RB test results for Iplex pipes compared to Brogden's results on U. K. PVC-U and PVC-A pipes.

The combined results of the tests performed at 3 and 19 Hz are shown [Fig. 9] with the initial stress amplitude plotted against cycles-to-failure. It was found that at the higher and lower amplitudes, the results for each material were largely independent of frequency. It was only in the intermediate range that the higher frequency resulted in a higher number of cycles to failure. That is, the curves were flatter in the mid-range for the tests performed at the higher frequency. Consequently, it is justifiable to use the higher frequency to generate results in the threshold region. The higher frequency was also adopted for the investigation into the effect of temperature on fatigue resistance.

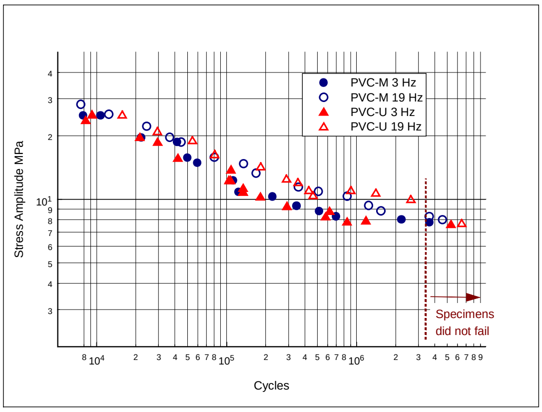

Figure 9. Initial stress amplitude versus cycles- to-failure for PVC-M and PVC-U at 20°C for test frequencies of 3 and 19 Hz

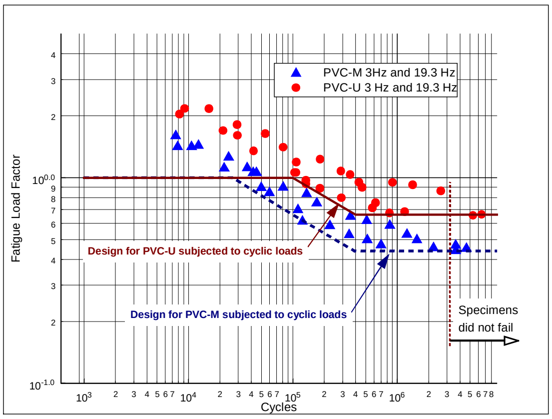

Figure 10. FLF versus cycles-to-failure for PVC-M and PVC-U at 20°C, together with proposed design model incorporating a threshold

The results [Fig. 9] have been re-presented [Fig. 10] as the FLF versus cycles-to-failure. To determine the FLF for PVC-M, the initial stress amplitude was divided by the design stress for PVC-M, 17.5 MPa. For PVC-U, the FLF was calculated by dividing the initial stress amplitude by 11.6, this being the mean of the two design stresses nominated for the product in AS/NZS1477. It can be seen that whilst the materials are indistinguishable [Fig. 9] when plotting stress amplitude versus cycles-to-failure, the same is not true when plotting FLF versus cycles-to-failure because of the differences in the design stresses. Superimposed on the graph is a proposed design against fatigue at ≤ 20°C, incorporating a threshold such that, if the stress amplitude is less than the lower value for PVC-M or PVC-U as appropriate, no fatigue derating is necessary.

Using equation 2, the initial stress intensity factor amplitude, ΔK, was calculated from the initial stress amplitude, applied moment and specimen dimensions. Plots of ΔK versus cycles-to-failure for both materials at 20°C, 30°C and 40°C are presented in Fig. 11. Raising the test temperature to 30°C reduced the fatigue resistance of both PVC-M and PVC-U to a similar extent. Moreover, the apparent threshold was similarly reduced. Increasing the test temperature to 40°C further reduced the fatigue resistance but the difference between 30°C and 40°C is less than between 20°C and 30°C. The apparent fatigue threshold at 20°C is approximately 0.3 MPa.m$^{0.5}$ whilst at 30°C the value is approximately 0.2 MPa.m$^{0.5}$. These results are consistent with Radon (20) who reported a threshold, ΔK_{th}, of 0.32 MPa.m$^{0.5}$ and Kim et al (21) who tested PVC-U at 32°C.

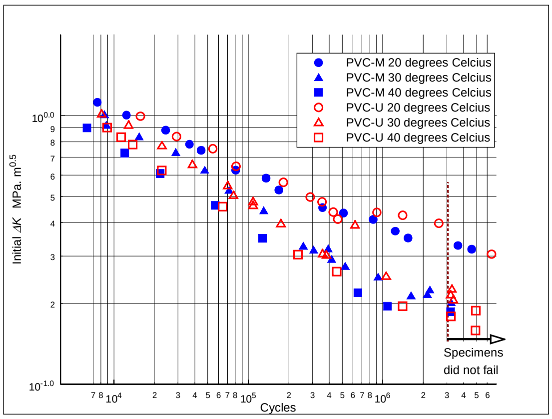

Figure 11. Initial stress intensity factor amplitude versus cycles-to-failure for PVC-U and PVC-M at 20°C, 30°C and 40°C.

The results for the two materials are re-presented [Fig. 12] as Fatigue load factor versus cycles-to-failure, together with the proposed design-against fatigue for pipelines operating at temperatures above 20°C. For the sake of simplicity, the same relationship between FLF and cycles-to-failure has been maintained in both Figures 10 and 12, with only the thresholds differing. This makes the proposed design at the lower temperature (≤ 20°C) more conservative in the region before the threshold. The proposed threshold values are given in Table 1.

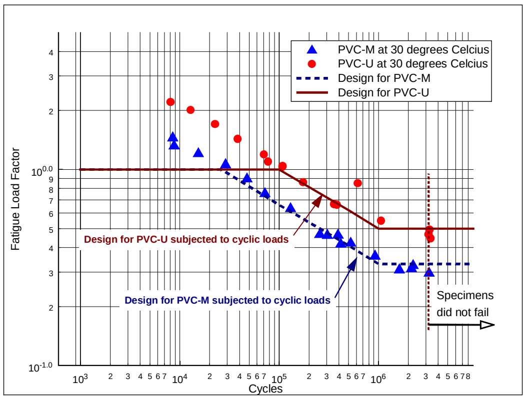

Figure 12. Fatigue load factor versus cycles-to-failure for PVC-M and PVC-U at 30°C, together with proposed design against fatigue.

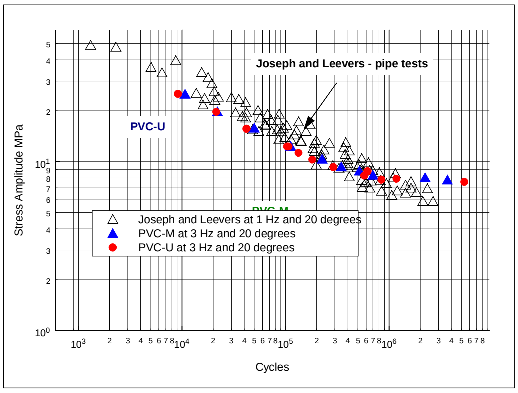

Figure 13. Initial stress amplitude versus cycles-to-failure for PVC-M and PVC-U RB tests compared to Joseph and Leevers' pipe tests.

A comparison has been made of the results obtained at a temperature of 20°C and a frequency of 3 Hz for rotational bending tests on PVC-M and PVC-U and Joseph and Leevers' results obtained by pressure testing PVC-U pipes [Fig. 13]. As expected from an examination of Figures 5 and 8, the rotational bending results of PVC-U and PVC-M closely approximate Joseph's and Leevers' results. The data has been re-presented as ΔK versus cycles-to-failure [Figs. 14 and 15]. The values of ΔK for the pipe were calculated according to equation 3 (11) assuming an inherent, semicircular flaw of size 0.5 mm or 0.2 mm, located on the inside surface of the pipe The smaller the assumed flaw size in the pipes, the greater the difference between the results of the pipe pressure tests and the PVC-U and PVC-M RB tests.

$$\Delta K = F_e\left(\frac{a}{b},\frac{a}{t}\right)\left(1+\frac{\Delta p}{\Delta \sigma}\right)\Delta\sigma(\pi a)^{0.5} \qquad (3)$$

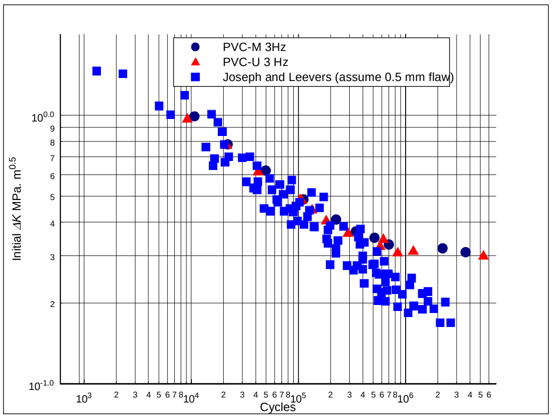

Figure 14. Initial stress intensity factor amplitude for RB testing of PVC-U and PVC-M compared to pipe tests (11) assuming an inherent flaw size of 0.5mm.

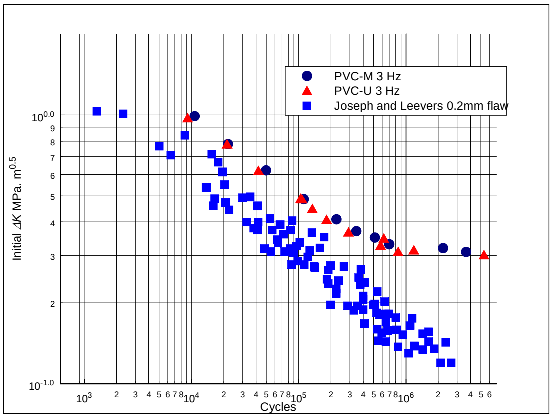

Figure 15. Initial stress intensity factor amplitude for RB testing of PVC-U and PVC-M compared to pipe tests (11) assuming an inherent flaw size of 0.2mm.

TABLE 1 Threshold fatigue load factors for PVC-U and PVC-M

Material	**Threshold Fatigue Load Factor**	
	Up to 20°C	Temperatures > 20°C
PVC-U	0.66	0.5
PVC-M	0.44	0.33

CONCLUSIONS

A number of conclusions can be drawn from this work.

- The PVC-U and PVC-M pipe materials tested exhibit the same cyclic fatigue behaviour. As a consequence, the same design philosophy can be applied to both PVC-U and PVC-M pipes. However, because PVC-M pipes are designed to operate at higher stresses than PVC-U, derating begins at a lower number of cycles.

- The slope of the stress-amplitude versus cycles-to-failure plot was similar to that reported by Joseph and Leevers and the lower bound published by Joseph.

- The Australian philosophy of basing the design against fatigue on Joseph’s lower bound is conservative, especially when compared to the U.K. Water Industry Specification.

- Rotational bending has been found to be a convenient means of investigating the fatigue threshold behaviour because reproducible results can be quickly generated, even at low stress amplitudes. Almost identical results were obtained in two independent laboratories.

- Results of tests at 3 and 19 Hz were similar in both the high and low stress amplitude regions. The higher frequency is therefore valid for investigating the threshold region. However, in the intermediate stress range at the higher frequency, higher cycles-to-failure were achieved.

- It is appropriate to incorporate a threshold into design codes for PVC-U and PVC-M pipes subject to cyclic loading. If a pipeline can be designed and operated so that the pressure amplitude is below the threshold, there is no cause to derate for fatigue.

- Both PVC-U and PVC-M exhibited a lower fatigue threshold at 30°C than at 20°C. It is therefore appropriate to apply a lower threshold value for pipelines operating at elevated temperatures.

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