How to Design Against Long Running Cracks in Plastic Pipe for Water Applications

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OUTLINE

- What is Rapid Crack Propagation (RCP)
- RCP Test Methods for Plastic Pipe
- RCP Test Data for PE and PVC Pipe
- RCP Field Failure Case Study
- Conclusions
What is Rapid Crack Propagation (RCP)?

- Rapid Crack Propagation is a very fast fracture. Crack speeds up to 1800 ft/sec (600 m/sec) have been measured in PVC-U. These fast cracks can travel very long distances.

- RCP cracks can initiate at internal defects or at cracks that might form during an impact event, butt fusion failure, tapping operation or other cause.

- RCP generally occurs in pressurized systems with enough stored energy to drive the crack faster than the energy is released.
Rapid Crack Propagation (RCP) – Engineering Property

- RCP is an engineering performance property of the plastic or metal pipe material.
- Various piping materials will behave differently when an RCP event occurs.
- For some ductile materials, like PE, the rapid crack travel can be arrested because of the toughness of the material.
- For other materials that are more brittle, the pipe can shatter during an RCP event or can run for over one thousand feet.
PE Pipes

• PE is a semi-crystalline plastic material that is well above its glass transition temperature, and is not very susceptible to Rapid Crack Propagation due to its toughness

• There have been very few reported RCP failures in PE pipe used in water applications and Pat Leervers, a leading researcher, reports none in the past twenty years

• In most European countries the amount of PE pipe used for all water applications varies from 50% to 90% - PE materials used in Europe are the same PE materials used in the US
PVC is an amorphous plastic material that is below its glass transition temperature, and thus is in a “glassy” or “brittle” state.

In the US, there have been Rapid Crack Propagation failures that have occurred in bell-and-spigot joined PVC pipe. These cracks typically arrest at the B&S joint.

Recently, multiple Rapid Crack Propagation incidents have occurred in PVC pipes joined by the butt fusion method. These cracks can travel for hundreds of feet through the BF joints.
Selection of Known PVC RCP (Rapid Crack Propagation) Field Failures

<table>
<thead>
<tr>
<th>RCP Failure Location</th>
<th>Date of RCP Failure</th>
<th>Pipe Size &amp; DR</th>
<th>Length</th>
<th>Joined by Butt Fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Park, FL</td>
<td>2004</td>
<td>8&quot; DR 18</td>
<td>200 ft</td>
<td>Y</td>
</tr>
<tr>
<td>Collier County, FL</td>
<td>2007</td>
<td>30&quot; DR 25</td>
<td>1100 ft</td>
<td>Y</td>
</tr>
<tr>
<td>Collier County, FL (#2)</td>
<td>2008</td>
<td>30&quot; DR 25</td>
<td>600 ft</td>
<td>Y</td>
</tr>
<tr>
<td>Danville, CA</td>
<td>2006</td>
<td>20&quot; DR 18</td>
<td>400 ft</td>
<td>Y</td>
</tr>
<tr>
<td>Clay County, FL</td>
<td>2008</td>
<td>20&quot; DR 18</td>
<td>600 ft</td>
<td>Y</td>
</tr>
<tr>
<td>Clay County, FL</td>
<td>2008</td>
<td>20&quot; DR 18</td>
<td>1600 ft</td>
<td>Y</td>
</tr>
<tr>
<td>Xenia, IA</td>
<td>2008</td>
<td>20&quot; DR 18</td>
<td>1100 ft</td>
<td>Y</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>2009</td>
<td>8&quot; DR 25</td>
<td>200 ft</td>
<td>Y</td>
</tr>
<tr>
<td>Greencastle, IN</td>
<td>2007</td>
<td>10&quot; DR 21</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>Green Bay, WI</td>
<td>2011</td>
<td>16&quot; DR 18</td>
<td>300 ft</td>
<td>Y</td>
</tr>
<tr>
<td>Chatham, IL</td>
<td>2011</td>
<td>18&quot; DR 25</td>
<td>850 ft</td>
<td>Y</td>
</tr>
</tbody>
</table>
Rapid Crack Propagation Field Failure in 30” DR 25 PVC Pipe

Duvall/Edwards reported RCP failure due to contractor error
Rapid Crack Propagation Field Failure in 20” DR 18 PVC Pipe

Reported cause of RCP to be due to contractor error
RCP Crack Travels Through Butt Fusion Joint in 30” DR 25 PVC

Malcolm Pirnie, Inc Report – April 2010
Need to Design to Prevent RCP

- RCP failures no longer occur in PE water pipes.
- RCP failures can occur in PVC pipe joined by bell-and-spigot, but the cracks typically only travel a few feet to the next joint.
- Since long-running RCP cracks can occur in butt fused PVC pipe, we need to understand the RCP phenomenon so that we can design the pipeline to prevent RCP failures from occurring.
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RCP Test Methods

- Full Scale (FS) Test – ISO 13478
  - long pipe samples
  - very expensive

- Small Scale Steady State (S4) - ISO 13477
  - smaller pipe samples
  - test done in a laboratory
  - easier to get data and correlates to FS test
S4 RCP Critical Pressure
S4/Full Scale Correlation per ISO 13477

\[ P_{c,FS} = \text{Full Scale Critical Pressure} \]

\[ P_{c,FS} = 3.6 \, P_{c,s4} + 2.6 \, \text{bar} \]

Where the correlation from S4 to FS has not been established, the test method recommends this equation.
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S4 Critical Pressure – PE
Pressure

To prevent RCP, limit the working pressure such that:

\[ P_{\text{max}} < P_{c,FS} \]
FS Critical Stress – DR 11
(Examples based on Dr. Leever’s* data for PE 80)

\[ P_{c,FS} = 3.6 \ P_{c,S4} + 2.6 \ \text{bar} \]

\[ P_{c,FS} = 3.6 \ (3 \ \text{bar}) + 2.6 \ \text{bar} \]

\[ = 13.4 \ \text{bar} \]

\[ P_{c,FS} = 194 \ \text{psig for DR 11 PE pipe} \]

\[ = 970 \ \text{psi critical stress} \]

Pressure Rating – DR 11
Example New PE 4710 Pipe

1) \[ PC = 2 \times (HDB) \times (DF) / (DR - 1) \]
   \[ = 2 \times (1600 \text{ psi}) \times (0.63) / (11 - 1) \]
   \[ PC = 200 \text{ psig} \]

2) Maximum pressure = 2XPC = 400psig for occasional surge

3) If the Full Scale RCP Critical Pressure = 650 psig for DR 11

4) Then, the WP is limited by the PC and is 200 psig for DR 11 PE 4710 pipe.
S4 Critical Pressure – PVC-U
FS Critical Stress DR 19 PVC-U (based on Dr. Leever’s data)

\[ P_{c,FS} = 3.6 \cdot P_{c,S4} + 2.6 \text{ bar} \]

\[ P_{c,FS} = 3.6 \cdot (1.6 \text{ bar}) + 2.6 \text{ bar} \]

\[ = 8.36 \text{ bar} \]

\[ P_{c,FS} = 121 \text{ psig for DR 19 pipe} \]

\[ = 1100 \text{ psi critical stress} \]
Pressure Rating – Example DR 19 PVCU

1) \[ PC = 2 \times (\text{HDB}) \times (\text{DF}) / (\text{DR} - 1) \]
   \[ = 2 \times (4000 \text{ psi}) \times (0.5) / (19 - 1) \]
   \[ PC = 222 \text{ psig} \]

2) Full Scale RCP Critical Stress = 1100 psi
   \[ Pc_{FS} = 121 \text{ psig for DR 19} \]

   \[ P_{\text{Max}} < P_{c,FS} \text{ so, } P_{\text{max}} < 121 \text{ psig} \]

3) In this case the \( P_{\text{Max}} \) is limited by RCP.
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Butt fused 18” DR 25 PVC pipe was held at a pressure of 60 psig for a few days – no problems.

For PVC pipe, based on S4 RCP data from Dr. Leevers and the ISO S4/FS correlation equation, the full scale critical pressure for DR 25 pipe is 91 psig (1100 psi).

When the pressure for this 18” DR 25 PVC pipe was increased, a crack initiated for some reason. The crack propagated by RCP approximately 850 feet, going through 21 PVC butt fusion joints.
Pressure Rating – DR 25 PVC

1) \( PC = 2 \cdot (HDB) \cdot (DF) / (DR - 1) \)
   \[ = 2 \cdot (4000 \text{ psi}) \cdot (0.5) / (25 - 1) \]
   \[ PC = 165 \text{ psig} \]

2) Full Scale RCP Critical Stress = 1100 psi
   \( Pc,_{FS} = 91 \text{ psig for DR 25} \)

\( P_{MAX} < Pc,_{FS} / 1.5 \)
\( PR = 60 \text{ psig} \)
Leak test pressure = 90 psig

In this case the Pressure is limited by RCP and is < 91 psig for DR 25 PVC pipe.
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Preventing Rapid Crack Propagation in PE Pipe

- The best way to design against a Rapid Crack Propagation occurrence in PE pipe is to select a material that has high resistance to RCP.

- Most PE materials have high resistance to RCP. The RCP Critical Pressure is generally higher than the maximum surge pressure allowed.

- Certain high performance PE 4710 materials, the RCP critical pressure is over 650 psig.
Preventing Rapid Crack Propagation in PVC-BF Pipe

- The RCP Critical Pressure for butt fused PVC pipe can be only half of its pressure rating.

- **RCP Full Scale Critical Pressure > Maximum Surge Pressure**
  
  \[ P_{\text{MAX}} = 1.6 \times \text{PC for C900} \]

  Need to lower the Pressure Rating, or

- Water engineer needs to use thicker wall pipe (lower DR pipe).
Dimension Ratio (DR)

“Although it is difficult to estimate the maximum crack speed for a particular material, experimental data from transducer measurements give 600 ms\(^{-1}\) for PVC-U and 300 ms\(^{-1}\) for PE-80 at 3° C just above the critical pressure. These wave speed values correspond to a minimum DR 13 for PVC and DR 29 for PE-80. Although such high DR’s are rarely seen in PE-80, almost all PVC pipe is 'thin-walled' (at least higher than DR 13) and as such is capable of sustaining RCP in 100 percent water pressurized pipe.”

Ref: Greenshields and Leevers, 1996
Key Benefits of Plastic Pipe Compared to Metal Pipe

- No corrosion
- Excellent long-term performance
- Lower total installed cost
- Easy to join - No leaks with butt fusion
- Easy to install
- Lighter weight
- Easier to handle
Conclusion - Future

- Whether PVC or PE pipe, the future is very bright for plastic pipe as a key piping material to replace the current failing metal water piping infrastructure.

- With knowledge of Rapid Crack Propagation, water design engineers can design their plastic water pipe systems to avoid long running cracks, and have a safe, reliable and cost-effective plastic piping system for their water pipe needs.
THANK YOU