DERIVATION OF UNIAXIAL STRESS-STRAIN CURVES FOR CAST IRON FROM SAMPLES TESTED IN FLEXURE

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ABSTRACT

Cast iron samples, tested in flexure as part of an ongoing programme of investigation into the Weibull properties of a range of cast irons have been assessed in a manner such that the tensile and compressive properties may be predicted from the response of the sample in bending. These samples have been taken from in service cast iron water pipes and have been only minimally processed such that corrosion products and the like have been left intact. Initial investigations show that this methodology represents a realistic technique for extracting such data from materials that might be problematic to test in tension or compression.

Introduction

Cast iron is a material that still has significant usage in the water industry. Although cast iron pipes, both distribution and trunk mains, are being phased out, a significant portion of current pipe networks are still comprised of the aging cast iron infrastructure that can be 50 to 150 years old. The cast iron pipes display a range of microstructures which, unsurprisingly, is related to their manufacturing process (pit cast and spun cast). Since it is prohibitively expensive, time consuming and too disruptive to replace this infrastructure in one programme of work, it is necessary to understand the properties of the remaining pipes so that replacement work can be focused in the first instance on areas of critical importance (Rajani and Makar [1]). Previous work has examined several aspects of the in-service conditions of distribution cast iron water pipes (Atkinson et al [2] and Belmonte et al [3]).

In the current research, Weibull methods have been used to assess the condition of mains water pipes from three locations in the London area. This has been linked to a study of the microstructure of the pipes. Further, a method developed by Crocombe et al [4] has been applied to test data derived from four-point bend (4PB) tests of cast iron samples. This method allows uniaxial stress-strain curves to be derived from strain measurements taken during the 4PB test.

Theory

A specimen in bending will be subjected to both tensile and compressive forces. By observing these behaviours it is possible to comment on these properties as if the material had been tested in either tension or compression. In the method of Crocombe et al [4] it is assumed that the strain varies linearly through the sample such that the strain at a point \( y \) from the neutral axis of a sample of thickness \( t \) may be determined by:

\[
\varepsilon = \frac{E_t - E_c}{t} y
\]

The stress is considered in incremental quantities, such that the maximum stress is equal to the maximum stress of the previous increment, which will now be observed at a distance \( \omega \) from the surface plus the stress observed between \( \omega \) and the surface. Both tension and compression curves can be derived using equations 1 and 2 in which a typographical error in the original paper has been corrected.

\[
\sigma_{t(i)} = \frac{M_i - M_{i-1} \left[ 1 - \frac{\omega_{t(i)} + \omega_{c(i)}}{t} \right]^2}{\sigma_{t(i-1)} \omega_{t(i)} \left[ \frac{t}{2} - \frac{\omega_{t(i)}}{3} - \frac{\omega_{c(i)}}{6} \right] + \sigma_{t(i-1)} \frac{\omega_{c(i)}^2}{6}}
\]

\[
\sigma_{c(i)} = \frac{\omega_{t(i)}^2 \left[ \frac{t}{2} - \frac{\omega_{t(i)} + \omega_{c(i)}}{3} \right]}{2}
\]
\[ \sigma_{c(i)} = \frac{-1}{\omega_{c(i)}} \left[ \sigma_{c(i-1)} \omega_{c(i)} + \sigma_{c(i-1)} \omega_{c(i)} + \sigma_{c(i)} \omega_{c(i)} \right] \quad (3) \]

Where \( \sigma \) is a stress and \( M \) a bending moment, The subscripts \( t \) and \( c \) refer to tension and compression respectively, whilst \( i \) relates to the current increment.

The values for \( \omega_t \) and \( \omega_c \) are determined from the experimental values of strain observed at the tension and compression faces through equations 4 and 5:

\[ \omega_{t(i)} = \frac{t}{(\varepsilon_{t(i)} - \varepsilon_{t(i-1)})} \cdot [F_{t(i)} - F_{t(i-1)}] \quad (4) \]

\[ \omega_{c(i)} = \frac{t}{(\varepsilon_{c(i)} - \varepsilon_{c(i-1)})} \cdot [F_{c(i)} - F_{c(i-1)}] \quad (5) \]

Several stress-strain curves derived by this method are presented in the results section, below. Each data point of the derived curves is the result of averaging ten data points prior to the calculations. This is a necessary step since otherwise the curve oscillates over a significant range. This provides a balance between smoothing, whilst still allowing for a realistic interpretation of the data. In some cases even this very basic smoothing technique is insufficient. It can therefore be necessary to use lines of best fit rather than the original data.

**Experimental**

Plates cut from three pipes (details presented in table 1) have been processed to produce 10 specimens each, which have been tested in four-point bending (Figure 1), as part of larger study to investigate the Weibull properties of a range of cast irons in a range of conditions, from the near pristine to the heavily corroded. Of these specimens, 3 randomly selected specimens in each set have been strain gauged (using Vishay General Purpose strain gauges) on both the tension and compression faces. Flexure testing was carried out using an Instron 1185 with a 1000 kN load cell. At this stage testing has been carried out with the external surface always in compression and the internal surface in tension.

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Gauge length, mm</th>
<th>Width, w</th>
<th>Thickness, t</th>
<th>( \phi )</th>
<th>Condition</th>
<th>Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>31.9</td>
<td>2.2</td>
<td>32.3</td>
<td>0.5</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>32.1</td>
<td>1.6</td>
<td>24.4</td>
<td>3.1</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>250</td>
<td>30.8</td>
<td>0.7</td>
<td>27.5</td>
<td>0.5</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Processing of the specimens has been kept to a minimum and where possible corrosion products have been left intact. Obviously this is problematic when attempting to attach strain gauges and it has been necessary to strip the surface back to nominally bare metal. In doing this some graphitisation was observed at the surface, in varying degrees of severity. Disruption of the surface layers was kept to a minimum and hence instead of (potentially) removing several millimetres of material, the minimum was removed and a thin layer of two part epoxide filler was applied. This has been carefully sanded back to expose bare metal, whilst keeping a flat and even surface to which the strain gauge were applied.

**Results**

It is well known that cast iron has differing tensile and compressive properties. This is highlighted in Fig. 2 (derived from experimental data for pipe 1) which shows the movement of the neutral axis towards the compression face during a flexure experiment.

Fig. 3 compares the raw data taken from the tension and compression faces of the strain-gauged specimen with the tension and compression data derived from equations 2 and 3. As has already been stated, cast iron shows different properties, being stiffer in compression. Further, this behaviour is observed to be more extreme in the derived uniaxial stress-strain curves; this again fits with what is expected since tension/compression tests typically show higher values for yielding than observed in flexure. A closer examination of \(0 < \varepsilon < 0.1\%\) is presented in Fig. 4. It can be seen that there is some non-linearity, particularly in the case of the tensile data.

Finally, the uniaxial stress-strain curves are consistent with data reported for cast irons by Walton and Opar [5]. Table 2 presents a comparison of the three pipes with this data. It should be noted that the compressive strengths presented for the current specimens are based on a flexure specimen that has failed in tension. Hence, the actual compression strengths are likely to much higher than those found in Table 2.
Deflection of Neutral Axis

Figure 2. Movement of the Neutral axis in a flexure specimen

Figure 3. Stress-strain data for a specimen tested in four point bending, compared with derived uniaxial data. Pipe 1)
Figure 4. Stress-strain data for a specimen tested in four point bending, compared with derived uniaxial data. (Pipe 1)

Figure 5. Comparison of derived stress-strain data for three specimens from Pipe 1
Table 2. A comparison of experimental and reported data

<table>
<thead>
<tr>
<th>Cast Iron</th>
<th>Tensile Strength (MPa)</th>
<th>Compressive Strength (MPa)</th>
<th>(Tensile) Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM A 48 Class</td>
<td>20</td>
<td>152</td>
<td>572</td>
</tr>
<tr>
<td>25</td>
<td>179</td>
<td>669</td>
<td>79-102</td>
</tr>
<tr>
<td>30</td>
<td>214</td>
<td>752</td>
<td>90-113</td>
</tr>
<tr>
<td>Pipe-1</td>
<td>1</td>
<td>130</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>170</td>
<td>78</td>
</tr>
<tr>
<td>8</td>
<td>127</td>
<td>330</td>
<td>70</td>
</tr>
<tr>
<td>Avg.</td>
<td>152</td>
<td>233</td>
<td>73</td>
</tr>
<tr>
<td>Pipe-2</td>
<td>1</td>
<td>120</td>
<td>180</td>
</tr>
<tr>
<td>7</td>
<td>104</td>
<td>192</td>
<td>77</td>
</tr>
<tr>
<td>Avg.</td>
<td>112</td>
<td>186</td>
<td>81</td>
</tr>
<tr>
<td>Pipe-3</td>
<td>3</td>
<td>165</td>
<td>180</td>
</tr>
<tr>
<td>6</td>
<td>130</td>
<td>290</td>
<td>70</td>
</tr>
<tr>
<td>9</td>
<td>140</td>
<td>310</td>
<td>77</td>
</tr>
<tr>
<td>Avg.</td>
<td>145</td>
<td>260</td>
<td>85</td>
</tr>
</tbody>
</table>

Summary and Concluding Remarks

Specimens of cast iron, tested in flexure have been strain gauged and the data collected used to derive tension and compression properties for the bulk material. These properties have been found to coincide with reported data. The method of Crocombe et al [4], which was initially derived for an adhesive specimen has been shown to have relevance to a wider range of materials. Whilst direct tension and compression tests still have a place, the analysis applied here to a flexure test represents a reasonably easy method for determining the tensile and compressive properties of bulk samples, which can be difficult to test in tension and compression. Further testing (including testing the external face in tension and the internal face in compression) is planned. Of more interest will be a greater level of comparison between the observed Weibull characteristics, the microstructure and the work presented here.

References