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On the condition assessment of cast iron trunk main: The effect of microstructure and in-service graphitisation on mechanical properties in flexure

D.A. Jesson [a],*, H. Mohebbi [a], J. Farrow [b], M.J. Mulheron [a], P.A. Smith [a]

[a] Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom
[b] Formerly of Thames Water Utilities Ltd. Reading, Berkshire RG1 8DB, United Kingdom

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ABSTRACT

The mechanical properties of cast iron used for trunk mains in the water industry have been studied. Specimens have been sourced from nine different pipes, which had been in service for up to 150 years before failure. The bulk microstructures of each cast iron have been analysed with regard to the graphite flake morphology and size. The stress–strain behaviours in tension and compression have been derived from specimens loaded in flexure. Flexural strength data have been obtained for 30 specimens from each pipe (three batches of 10 from different locations along the length and around the circumference of the pipe) and these data have been analysed using Weibull methods. The depth of graphitisation visible on the fracture surface of each sample has been measured. It is shown that the strength of the cast iron samples decreases with increasing depth of graphitisation. When the layer of graphitised material is of reasonably uniform thickness, the strength reduction is modest, but where the section loss is more local, the strength reduction is more significant — for some samples there is a reduction in strength of more than 50% when the depth of graphitisation exceeds 4 mm. Simple strength-of-materials and fracture mechanics approaches are shown to provide reasonable bounds for the data.

1. Introduction

Cast iron pipes have been used extensively in the water industry with great success for more than 150 years. However, an ageing cast iron infrastructure exists now [1] that requires targeted rehabilitation/replacement in order to reduce leakage and the incidence of catastrophic failures. The current work is part of an ongoing programme of research, the overall aim of which is to improve the understanding of the in-service aging of cast iron water mains and its consequences and implications for the water industry.

In previous publications [2,3] the condition and residual properties of *distribution* mains, which comprise pipes of diameter typically 4–8 in. (100–200 mm) and a wall thickness of 10–15 mm, have been considered. This work used Weibull statistics to characterise the strength distribution of sets of samples comprising lengths of pipe from a given street and sets of samples based on taking specimens from a single length of pipe. It was argued that in each case the effect of in-service corrosion (graphitisation) was to introduce a defect population which lowered the (mean) strength and increased the variability within the sample set compared to pipes in the as-manufactured condition. The relationship between pipe strength and the depth of corrosion measured on the fracture surface was shown [2] to be consistent with arguments based on either a loss-of-section model or on fracture mechanics, consistent with other studies in the literature [1,4–6]: variability in the data meant that it was difficult to draw conclusions regarding the applicability of the two approaches. It was suggested subsequently that changes in the Weibull modulus and the characteristic strength could be used as a basis for pipe/network condition assessment [7].

The aim of the present work, which is part of a larger study of cast iron trunk main properties (see e.g. [8] for fracture mechanics properties), is to carry out experimental studies of some of the materials issues relating to the condition assessment of the larger diameter cast iron *trunk* mains. These are typically between 12 and 48 in. diameter (around 450–1200 mm) and of much larger wall thickness—typically 30 mm, although with significant variation. (Other materials are in use but beyond the scope of the current work; larger mains are usually referred to as tunnels and will usually be constructed from concrete). The study includes microstructural characterisation and mechanical property measurement with a particular focus on the relationship between the strength and the depth of graphitisation. An important difference between the present work and previous work on distribution mains is that

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* Corresponding author. Tel.: +44 1483686299; fax: +44 183686291.
E-mail address: d.jesson@surrey.ac.uk (D.A. Jesson)

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in the present work, the effects of material non-linearity are considered in the analysis of the data. In the work on distribution mains it was argued, with reference to experimental data, that it could be neglected but this is not the case for the thicker sections tested here.

The structure of the paper is as follows. The next section describes the methodology, with sub-sections that detail (i) the pipe samples that were sourced, their microstructural characterisation and test specimen preparation, (ii) the flexural test method used to derive the stress–strain response and (tensile) strength values and (iii) the analysis of the strength data using Weibull methods. Following this, results are presented for the samples from the various pipes, in particular the strength data, which are presented statistically and in the form of strength as a function of depth of graphitisation. These are then interpreted in the light of the graphitised material morphology using simple mechanics models.

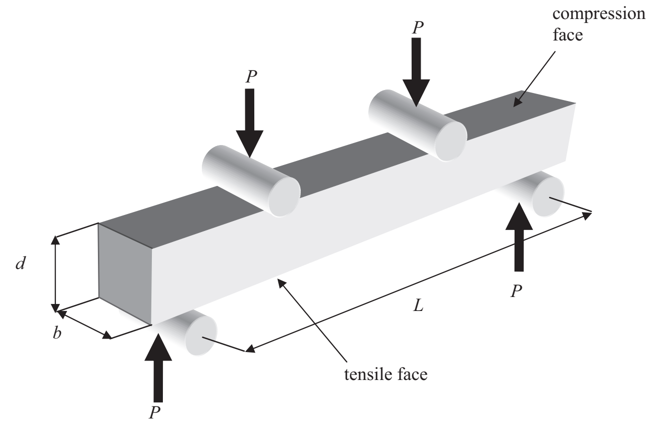

Fig. 1. Specimen orientation for four-point bend test. (The Tensile face of the bend specimen is the external face of the pipe).

2. Experimental methods and data analysis

2.1. Pipe samples

Three plates have been cut from each of nine lengths of water main, Pipes 1–9, with the exception of Pipe 8, where only two plates were available; details are presented in Table 1. In the case of Pipes 3 and 9, location material was still attached to the pipe on delivery. Such material, which is a mixture of clay and aggregate, can become chemically and/or mechanically interlocked with the corrosion products found at the surface of the pipe, and adhere so tenaciously that a layer of material is removed from the site with the pipe. To produce specimens from the plates, it was necessary to remove this layer. This was effected with mechanical methods in the case of Pipe 3, but in the case of Pipe 9 the layer was harder and more coherent. Instead, the layer in this case was removed electrochemically: the plate was placed in a solution of NaOH and made the cathode in a circuit.

All the plates have been cut mechanically to produce sets of specimens which have been tested in four-point bending (Fig. 1 and Section 2.3). The bend specimens were $d \times 30 \times 350$ mm; the depth (d) of the specimen was dependent on the full wall thickness of the original trunk main. Some variation in the specimen width occurred, as it was not possible to provide fine control of the cutting process with the equipment available.

2.2. Microstructural analysis

Samples of the full-wall thickness were cut, mounted in conducting Bakelite and polished in stages to give a 0.25 μm surface finish and examined optically using a Zeiss Axiophot optical microscope. The samples were then etched with 2% Nital (a solution of nitric acid in methanol) and re-examined.

Table 1
Details of the available pipes.

Pipe	(Nominal)ϕ/		(Nominal) wall thickness/mm	Age*/years
	in.	m		
1	48	1.22	28	82
2	42	1.07	32	~85
3	30	0.76	22	82
4	18	0.46	21	125
5	24	0.61	23	115
6	36	0.91	23	151
7	12	0.31	18	~70
8	18	0.46	22	~120
9	21	0.53	28	150

* Age is the duration from installation to removal from service and is to the nearest year, except for those pipes where the age is indicated as approximate and duration is less certain.

In the context of these materials, microstructure must also include the extent and variability of corrosion products, in particular graphitisation, which is the preferential removal of iron from the microstructure e.g. [9]. Rates of corrosion can vary and pipe of the same specification and age can remain in as cast condition or corrode through the full thickness of the pipe, depending upon local exposure condition. The extent, size and distribution of porosity, inclusions, ‘cold shuts’ and similar *ab initio* defects must also be considered. Such *ab initio* defects are predominately a function of manufacturing method but, particularly in the case of large sections are very difficult to control. Both corrosion and *ab initio* defects can lead to a (locally) weaker component. These points will be considered further in the results section.

2.3. Sample preparation and flexural test method

Flexure testing was carried out using an Instron 1185 with a 100 kN load cell. A set of ten specimens from each plate was prepared, with a total of thirty specimens produced from each pipe. Three randomly selected specimens in each set were strain gauged (using Vishay General Purpose strain gauges) on both the tension and compression faces. Processing of the specimens was kept to a minimum and where possible corrosion products were left intact. However, when attaching the strain gauges, it was necessary to strip the surface back, nominally to bare metal. In doing this, some graphitisation was observed at the surface, in varying degrees of severity. Disruption of the surface layers was minimised and hence, instead of (potentially) removing several millimetres of material, the least possible amount was removed. In some cases a thin layer of two part epoxide filler was applied, and carefully sanded back to expose a flat and even surface to which a strain gauge was attached. The most important consideration in this phase of the testing was to ensure that the strain gauge accurately recorded the strain observed at the outer face of the specimen.

2.4. Determination of stress–strain curves from flexural data

Cast iron has different stress–strain responses in tension and compression [10]. This means that at higher strains there is a non-symmetric stress distribution between the tensile and compressive faces of a specimen in bending and this exacerbates the problem of testing large samples which cannot easily be tested