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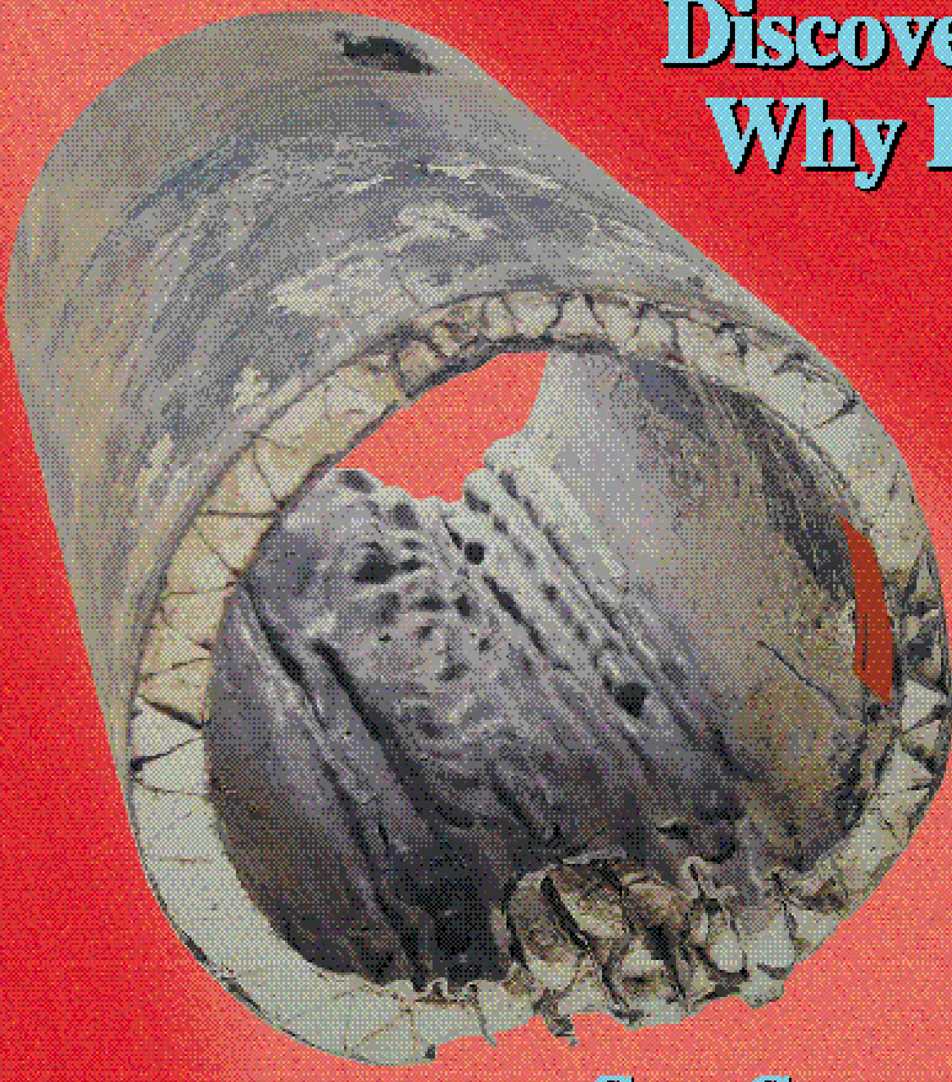
Discovering Why Pipes Fail



Core Competencies for Plumbing Engineers

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- Fire Protection: A Critique of FEMA's World Trade Center Report

Discovering Why Pipes Fail

By Steve Ferry

With this article we hope to impart some information regarding failure analysis (FA) methods in general, and failure analysis techniques including testing and analyses. The article also includes some specific examples of testing in support of failure analysis I have encountered in my 12 years at Hauser Laboratories, an independent materials science and product development testing laboratory.

One accepted definition of failure is when a component can no longer perform its intended function. Typical reasons for failure include design deficiencies, improper material choices, poor quality materials and processing, manufacturing, and assembly issues, as well as issues arising from the service environment. Whenever a component no longer performs its intended function, it is valuable to understand how and why the component has failed. Failure analysis is performed to obtain this understanding.

In today's manufacturing environment, where products typically progress from the design stage to manufacturing to market at a very rapid pace, some companies are overlooking the need for failure analysis and the economical benefits to be derived from performing failure analysis in the early stages. It is usually far cheaper to perform adequate failure analysis in the early stages of a product's life than it is to deal with product failures and possible litigation at a later date.

What it is, and why

Failure analysis is the science of understanding how materials and products fail. FA would require approximately the same steps as product development such as material selection, design and testing, and manufacturing. The objective of manufacturing is to produce a reliable product, and this is achieved through engineering and product development, which requires FA. Also, properly engineered and developed products may fail at a later time due to problems associated with service conditions, design, materials selection and specification, processing and assembly, packaging, or a combination of any of the above. FA thus requires a science-based approach to analyzing design and field failures to continually improve a product's reliability. FA would be required whenever a component fails due to structural integrity, fails to perform, or displays problems associated with materials compatibility. FA is used to determine the cause or causes of failure so changes can be made to prevent future failures.

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A complete FA starts with collection of background information and selection and preservation of samples. Background information will include any and all aspects of the failure including sample history such as service and manufacturing history, photographic records of the sample in service and/or during or after failure, and any abnormalities with the samples and/or environment. It is also valuable to inventory the samples available for inspection and testing at this stage.

Background information can also help to deduce the cause of failure. Information such as number and frequency of failures can indicate possible failure modes. The time at which a failure first occurs also can help determine possible failure modes. Information pertaining to manufacturing can suggest possible QA changes to eliminate failures. Data regarding the component's manufacturing history needs to be obtained. Data of this type is typically obtained from the manufacturer.

Other information regarding the component should be obtained such as material and product specifications, in-process manufacturing specifications, test specifications and methods, and installation and handling specifications. This information should be obtained from national code and specification groups such as ASTM, ANSI, UL, NSF, etc., or from product and retail groups. Also, the best example of what a component should look like is an un-failed exemplar. For testing purposes the best exemplar would be from the same production lot and mold, but other lots sometimes offer significant data.

As noted earlier, FA could be described as the alter ego of engineering during product development. Material selection, design, and processing are all part of the product development process, and are used extensively during FA. By making observations regarding the failure of the component, identifying possible failure scenarios, and researching applicable test specifications and methodologies, the failure analyst can then choose appropriate testing to confirm the hypothetical failure mode.

How to proceed

Near the beginning of any failure analysis, if possible, make observations of the failed component in the

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actual failure environment. Although this is not always possible due to uncontrollable factors, it is best because valuable information may be lost during removal or replacement of the failed component. If possible, at the failure site, make observations of what is failed and how. What is the geometry and physical location of the components involved? What is normal regarding these locations and what has changed? From this information one should be able to deduce possible failure scenarios.

This stage is sometimes merged with laboratory observations of the failed component if the failure site is altered or unavailable for observation. The component should be compared to an un-failed exemplar if possible, and analyzed to determine macroscopic fracture patterns, initiation sites, and possible fracture modes. Knowledge of applied stress fields is critical to interpretation of fracture propagation. At this stage the failure analyst would best consider themselves a Sherlock Holmes-like detective, gathering all possible clues from the evidence at hand. Clues gained during observation would include overall appearance, as well as any contributing factors

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such as mechanical damage, environmental concerns like heat, light, and chemicals. Photographic recording of this portion of the analysis is important, because some information which may be critical at a later time in the investigation may only be present in the photographic record.

During the course of a failure analysis, it is best to perform as much non-destructive testing as possible prior to performing any destructive tests. Non-destructive testing of samples includes observation and documentation, liquid penetrant inspection, electromagnetic and or ultrasonic inspection, and residual stress analysis using photoelastic techniques.

Testing that could be performed that would be predominantly destructive in nature consists of physical and mechanical properties testing of materials, chemical composition of materials, product performance and life tests performed on exemplar components, and microscopy of products performed on failed components, tested exemplar components, and unfailed components for comparison.

General mechanical testing could consist of tensile, shear, and compressive tests, and impact, fatigue, and fracture mechanics testing. Most of these tests could also be performed in static, dynamic, and cyclic test proto-

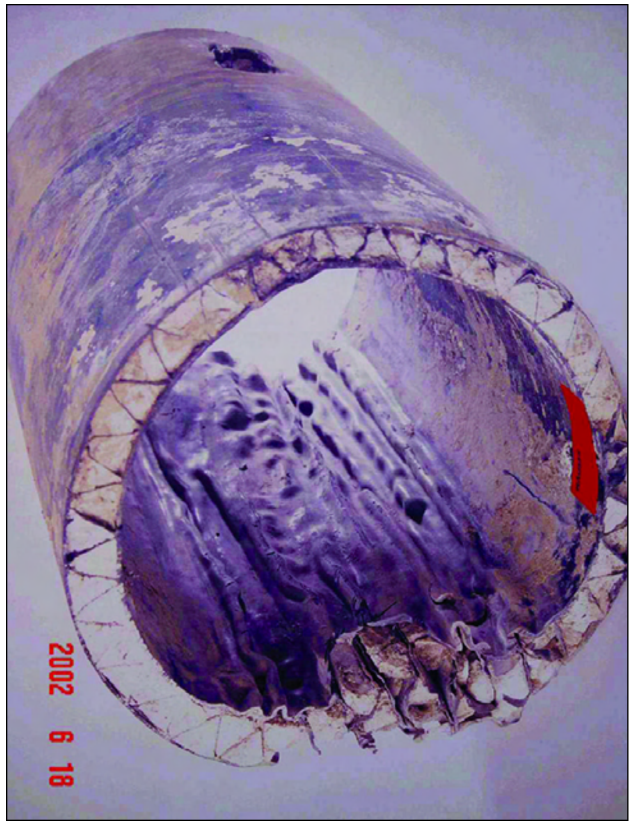

Figure 1 — Section of ABS truss pipe affected by long-term exposure to drycleaning solvents.

cols, also in various environmental conditions with various pre-test exposures, depending upon possible failure modes.

General physical properties testing could consist of density, hardness, residual stress, oxidative stability, and thermal properties such as melting point, crystallinity and glass transition using differential scanning calorimetry (DSC). Thermogravimetric analysis and thermo-mechanical analysis could also be performed to identify various physical properties.

General chemical properties testing is valuable to determine the chemical composition of the base material, and any additives, fillers, and possible contaminants. Various techniques employed could include FTIR (fourier transform infrared spectroscopy), chromatographic techniques such as GPC (gel permeation chromatography), HPLC (high performance liquid chromatography), GC (gas chromatography), etc., and other spectroscopic techniques such as NMR (nuclear magnetic resonance) and UV/VIS (ultraviolet/visible light spectroscopy).

Preserving the evidence

One of the most important aspects of any failure analysis is the preservation of any intact fracture surfaces. The fracture surface is best considered the smoking gun in any investigation. Without this aspect of the failure, it is

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difficult and sometimes impossible to confirm a failure mode. Any fracture surfaces should be protected from contacting hard, rough, and/or abrasive surfaces by careful handling and storage methods. Fracture surfaces should be protected against mechanical, chemical, and thermal damage. Often fracture surfaces will need to be cleaned prior to analysis by any method. It is imperative to clean with the least destructive method first.

The component and related fracture surfaces should be viewed first using low power stereo optical microscopy. Low power allows the failure analyst to gain an overall understanding of the component and failure area. Also, stereo microscopes are best because of the apparent three-dimensionality of the image. During this stage the analyst should attempt to determine if the fracture is ductile or brittle, the origin of the failure, and direction of fracture propagation. Determine possible small-scale specimens to be removed for analysis using other higher power microscopes.

For high power microscopic examination of fracture surfaces, scanning electron microscopy (SEM) is by far the best. Light microscopes have a very limited depth of focus, and transmission electron microscopes require very difficult sample preparation and/or replication techniques. SEM also has the ability to magnify to approximately 50,000x, with a large depth of focus at any magnification. SEM samples need to be conductive, so simple coating techniques may be required.

With the results of the above described testing and analyses in hand, the failure analyst can then put together the large picture of why the component failed. Some test results may indicate that an initial understanding of failure mode is not correct, and additional testing may be needed. In this instance, your initial photographic records and in-process notes are usually critical to developing and testing additional specimens to confirm a different failure mode.

The testing performed should be chosen to confirm the hypothesized failure mode, as well as gaining an understanding of what can be altered and improved to not have failures occur in the future, which is the ultimate goal of any failure analysis.

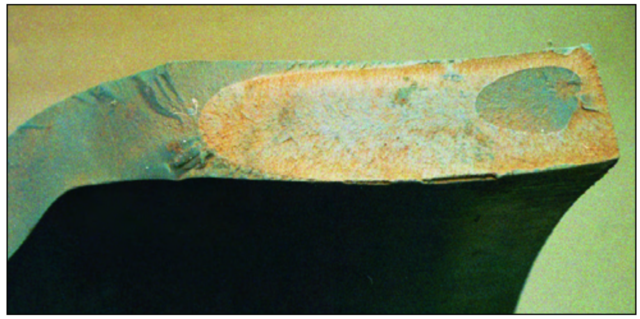

Figure 2 — Void manufactured in wall of PVC pipe (smaller circular area at upper right) which eventually caused fracture to catastrophically propagate.

Some examples

Following are a series of failure analyses performed by Hauser Laboratories which should provide a better understanding of the employment of the above-described failure analysis techniques.

Case Study #1: Product Misuse

Hauser received three samples of 12-inch nominal ABS truss pipe from a Texas utility district, which used the pipe in a sanitary sewer application. ABS truss pipe consists of a coextruded ABS shell filled with portland cement. Upon receipt, the samples were inspected and found to contain an axially oriented area of damaged ABS, such that under ring compression the pipe had buckled. This buckling reportedly occurred at the 6 o'clock position in the sewer system, which is consistent with a gravity flow system. The ABS appeared to be damaged due to chemical attack, and displayed evidence of softening, possibly due to exposure to solvents. The softened ABS had subsequently altered shape and dimensions (see Fig. 1).

Hauser performed a failure analysis, with one main component of the failure analysis being heated headspace gas chromatography (mass spectroscopy), HHGC-MS. The GC-MS test results indicated the presence of perchloroethylene, in quantities greater than 1000 ppm, in the wall of the ABS at the 6 and 12 o'clock positions. Trichloroethene was also found. It is known that perchloroethylene is used for drycleaning, and the damage to the sewer system was isolated to an area directly downstream from a commercial drycleaning operation. Subsequent testing by the municipality confirmed that the drycleaner was discharging solvents directly to the sanitary sewer system and was found liable for repairs.

Case Study #2: Manufacturing Defect

Hauser received one sample of fractured 16-inch nominal AWWA C905 PVC pipe from a contractor who had installed the pipe. The pipe sample had failed during an air pressure test prior to filling the system with water. The fracture was a single fracture at the bell end, which split into two separate fractures which later re-joined. The fracture was approximately 7 feet in length. This section was completely fractured out of the barrel of the sample.

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Figure 3 — Cyclic fatigue fracture of PVC tee used in water spraying system.

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After documentation and sectioning of the sample, it was noted that the fracture origin was near the lip of the bell. The fracture origin consisted of a void at the midwall of the pipe that accounted for approximately 50 percent of the wall thickness at this point (see Fig. 2). It was discovered that this void displayed fracture morphology within the void, indicating that the void was most likely formed during the bell forming process. This void constituted a manufacturing defect. The section of pipe was replaced with the costs borne by the pipe manufacturer.

The failures could have been eliminated by using a significantly more robust fitting and or thrust blocking of the tee and lever arm of the pipe branch to reduce or eliminate the stress.

Case Study #3: Poor Fabrication

Hauser received numerous samples of solvent cemented 4-inch nominal schedule 40 bell/spigot joints in PVC pipe. The joints were from a system used to transport a sodium hypochlorite solution. The system owner and user reported that the joints had leaked in service at an ambient system pressure of approximately 80 psi. The joints were sectioned and inspected. The inspection results were then compared to the requirements of an ASTM specification which describes how to correctly assemble PVC solvent cement joints. Numerous deficiencies were found, notably lack of complete insertion, inadequate fusion (possibly due to lack of primer use), incomplete coverage, and possible contamination of the glue (sand/dirt/debris). The system installer was required to return to the jobsite and make repairs without additional cost to the owner/user.

Case Study #4: Inadequate Design

Hauser received two samples of 2-inch nominal solvent cement PVC tee fittings which had failed in service. The tees were portions of a Florida amusement park ride where water jets were constantly cycled on and off. The tees branched vertically from the 2-inch supply line for approximately 6 inches, where the branch then changed directions 90 degrees (from the axis of the supply line). The system operated using recycled (potable) water. Hauser performed failure analysis, and in the process determined that the fitting samples displayed adequate workmanship of manufacture and assembly, adequate material strength, and were manufactured from an appropriate material. The fractures indicated a stress field was present which caused fracture that could only have come from operation of the system. This stress field ultimately caused a fatigue type failure in the fittings due to torsional loading of the fittings through the 6-inch lever arm, caused by water hammer as the water was cycled on and off repeatedly. The failures could have been eliminated by using a significantly more robust fitting and/or thrust blocking of the tee and lever arm of the pipe branch to reduce or eliminate the stress. □

About the Author

Steve Ferry is a division manager with Hauser Laboratories, Boulder, Colo., where he is responsible for materials testing and the pipe testing laboratory. Mr. Ferry is a member of ASTM and ASM and has performed numerous failure analyses of piping components in his 12 years with Hauser. Mr. Ferry can contacted by sending email to s.ferry@hauserlabs.com.