Failure Analysis

If you don't know how it broke, you don't know how to fix it…

Failure analysis consists of investigations performed to find out how and why something failed. The necessity for understanding the actual reason for failures is absolutely required to avert recurrence and prevent a failure in existing similar equipment. The analysis will further the understanding and improvement of design, materials, fabrication techniques, and inspection methods.

Failure Analysis Sequence

Obtain Background Information

(1) Obtain part history and material information.
(2) Document component condition, including photography.
(3) Determine a failure analysis plan

Perform a Preliminary Evaluation

(1) Perform nondestructive testing when appropriate
(2) Photographically document results of nondestructive testing.
(3) Examine selected areas visually and by stereomicroscopy.

Perform a Material Evaluation

(1) Remove and examine selected areas by scanning electron microscopy in order to determine the failure mode.
(2) Section for microstructural analysis, chemical analysis, hardness, or mechanical testing. Photographically document the location of samples prior to excision.

Analyse Data and Prepare a Report

(1) Analyse data and compare to specifications
(2) Verify, in order of importance, the failure mode and contributing factors.
(3) Determine the contributing factor(s) and appropriate corrective action(s).

The failure analysis sequence is generally performed in order of increasing "destructiveness" of the test and/or sample removal. Significant deviation from this recommended hierarchy can preclude crucial evaluation techniques through damage caused by previous tests. Naturally, test methods may be added or deleted from this sequence with consideration given to the best order of desired analyses.

Part I: Obtain Background Information

Part Information:

Detailed information about a failed component is of tremendous benefit to the analyst, often facilitating selection of analytical methods to be employed and can, in some instances, provide insight into some of the potential factors which may have contributed to the failure. Certain test methods may be suggested by knowledge of the component's manufacturing history and this could lead to a quicker solution. Part information should include as a minimum:

- Applicable Specifications
- Manufacturing Information
- Part Number and Serial Number
- Part Drawings with a Bill of Materials

Service History:

The history of a failed part is also of great importance to the analyst, often serving to illuminate the causes of a failure. Even "typical" service, which may be ostensibly identical to similar units in similar conditions, may initiate failure due to apparently innocuous or mundane service differences which may not initially seem worthy of mention.

Investigation Planning and Sample Selection:

The planning portion of an investigation is crucial to determining the proximate cause(s) of a material failure. Proper planning can ensure an investigation is performed efficiently. Particularly in circumstances where a high visibility failure occurs or an assembly line shut down is imminent, careful planning is necessary to hasten problem resolution. Haphazard or unsystematic investigations can appear unprofessional and can be wasteful of time, effort and manpower.

Part II: Perform a Preliminary Examination

Visual Inspection:

All pertinent features should be examined, and thorough notes should be taken for each component associated with a failure analysis. Many macroscopic features and characteristics can be suggestive of certain failure modes and circumstances. Fracture surfaces can exhibit an identifiable origin, progression marks, direction marks, and post fracture damage, all of which can be significant to the failure.

Photographic Documentation:

All of the pertinent features of interest noted in the visual examination should be well documented. The component condition as well as any stamped information/part numbers should be illustrated. This should be done as soon as possible after failure, especially if ongoing corrosion or degradation of the fracture surfaces may be occurring. If smaller sections are to be excised for analysis, this step can document their locations and orientations. Photography is necessary as subsequent dissection of the sample may preclude further visual examination.

Nondestructive Examination:

Nondestructive examination (NDE) describes a family of analytical techniques which have been developed to evaluate materials without causing damage. Different methods can be used to detect various features and flaws, providing information which can be used to determine the cause of a materials failure.

Typical Nondestructive Examination Methods Used in Failure Analysis

Acronym	Technique	Information Provided
EC	Eddy Current	Detection of anomalies by differential electrical current response
MRI	Magnetic Resonance Imaging	Identification of features and structure via introduction of alternating magnetic fields
MT	Magnetic Particle Examination	Detection of surface and near surface flaws in ferromagnetic materials by flux leakage
PT	Penetrant Testing	Identification of flaws and cracks open to the surface in many materials via liquid retention
RT	Radiographic Examination	Identification of material flaws and features via density differences measured by penetrating radiation
CT	Computed Tomography	Radiographic information assembled to provide a three dimensional image of the location of flaws and features.
UT	Ultrasonic Examination	Detection of anomalies by differential reflection of ultrasonic pulses

Part III: Perform a Material Evaluation

"One test is worth a thousand expert opinions." - Anonymous

Although the above aphorism is not attributed to any particular source, its message is a very important one for the failure analyst. Thoroughness and diligence mandate that prudent material evaluation be performed as an integral part of any failure process. Many individuals with or without qualifying experience feel sufficiently confident to render sophisticated failure analysis judgments without performing the requisite testing. Absurd as this practice may sound, it is done every day. Naturally, a wise analyst will invariably perform the proper tests dictated by the physical evidence of an investigation. A general rule of thumb to follow in this regard is that failure analysis minus the analysis is just a failure.

Failure Analysis – Analysis = Failure

Equally deleterious to the failure analysis process as not performing an analysis is not performing all of the necessary tests. Sometimes a "target of opportunity" approach is taken, wherein an analyst will stop the investigation at a point when a discrepancy is found (i.e., improper chemical composition, low mechanical strength, etc.). The conclusions would then be composed around this hypothesis based upon the incomplete investigation. Most material failures are complex and may contain significant contributory causes. Although it may be economically attractive to conduct a minimal evaluation, the proximate failure cause may be missed and improper recommendations may be made as a result of this ill-advised practice.

Environmental Testing:

Many types of environmental tests have been developed and are often used in failure analyses. These tests can simulate the corrosivity and temperature extremes experienced by a component in service. They can be performed on a failed part or on an exemplar part which has been processed similarly. Testing can reveal material behavior which can provide insight into the cause of a failure.

Mechanical Testing:

Mechanical testing has long been a mainstay of failure analysis, since mechanical properties are generally specified during the design phase of manufacture. These properties have been historically measured by material suppliers and are often reported to the end user. Comparison of properties measured on a failed material can often be directly compared to pertinent specifications and prior property data. Discrepant strength levels can be determined and in many cases degradation of these properties during service can be identified.

Typical Mechanical Testing Methods Used in Failure Analysis

Test	Information Provided
Bend	Measures ductility of base materials and weldments
Hardness	Measurement of a material's resistance to indentation. Knoop, Vickers, Rockwell are examples for metals, Durometer for polymers and some composites.
Compression	Test which measures a material's inherent resistance to fracture under compressive loading. Compression modulus can be calculated.
Creep/Stress Rupture	Test which measures the resistance to rupture under sustained stress conditions. Typically run in tension to determine creep resistance.
Drawability	Measures the formability of a material to determine its suitability for severe forming during manufacturing.
Fatigue	Cyclic loading test to determine a material's fatigue resistance.
Flexure	Three or four point bending test which measures ductility.
Impact	Rapid point loading test which determines the impact resistance or toughness of a material. Test is often performed at simulated service temperature. (Charpy V-Notch, Izod, etc.)
Shear	A mechanical test which measures a material's resistance to fracture when shearing loads are applied. Most commonly performed as single or double shear methods.
Tension	Mechanical test which pulls a material apart and can determine the ultimate tensile strength, yield strength, elongation, reduction in area, modulus of elasticity and other properties.
Torsion	Mechanical test which loads a material in a twisting manner to measure its strength in torsion.

Chemical Analysis:

Chemical analysis is an integral part of an investigation as it indicates whether a component is made of the specified material. Subtle variations in composition can often dictate the strength and property values which processing can attain. In addition, relatively low amounts of impurity elements can cause significant changes in these same properties.

Microstructural Analysis:

Examination of cross sections of materials involved in a failure can provide important insight into the probable cause of the incident. One of the basic expressions of materials science can be illustrated as follows:

Failure Analysis – Analysis = Failure

Determination of material structure can indicate the likely mechanical and physical properties of a component. Similarly, this examination can reveal crucial processing information which may indicate incorrect or incomplete heat treatment or other required structural alteration. Microstructural analysis can reveal macrostructure, such as depth of surface hardening,banding, or flow directionality, and it can also reveal microstructure, such as grain size and the phases present, or orientation of fiber reinforcements. Carefully prepared cross sections from the identified fracture origin can show inherent defects or inhomogeneities which caused or contributed to the failure.

In many cases, the skill of the analyst is key in revealing the critical evidence that leads the analyst to the correct solution. Poorly prepared specimens can ruin the analysis by destroying critical inclusion, porosity, or other crucial evidence.

Environmental Testing:

Fractography, which is generally performed with the aid of a stereoscope along with an electron microscope, is an examination which can determine the failure mode(s) of a component. As such, this is an indispensable tool for the analyst as this information can not be obtained by any other testing technique. Using magnifications as high as 10,000X, fractography can reveal many telltale features which can not be seen using standard light microscopy. The limit of resolution of a microscope is the wavelength of the imaging illumination, hence visible light would exhibit far less resolution than electron microscopy due to its higher wavelength. Electron microscopes can also offer excellent depth of field which is a boon to morphological identification.

Typical Chemical Testing Methods Used in Failure Analysis

Acronym	Technique	Information Provided
AA	Atomic Absorption	Analysis of dissolved materials using a gaseous flame.
AES	Auger Electron Spectroscopy	Composite analysis of surface layer including depth profiling.
DSC	Differential Scanning Calorimetry	A measure of heat flow related to temperature.
EDS	Energy Dispersive X-ray Spectroscopy	Chemical analysis of small features and particles in the electron microstructure.
ESCA	Electron Spectrometry for Chemical Analysis	Surface chemical analysis.
FTIR	Fourier Transform Infrared Spectroscopy	Qualitative identification of materials using infrared light.
GC	Gas Chromatography	Quantitative analysis of organic materials after volatization.
GDS	Glow Discharge Spectroscopy	Analysis of metallic materials using arc vaporization.
GPC	Gel Permeation Chromatography	Form of LC for molecular weight distribution of polymers.
IPC	Inductively Coupled Plasma Spectroscopy	Analysis of dissolved materials using a plasma arc.
LC	Liquid Chromatography	Quantitative analysis of dissolved materials using separation techniques.
MS	Mass Spectroscopy	Detection of mass units of organic materials using a magnetic field.
OES	Optical Emission Spectroscopy	Analysis of metallic materials using arc vaporization.
RS	Raman Laser Spectroscopy	Qualitative identification of organic chemicals using Raman absorbance.
SIMS	Secondary Ion Mass Spectroscopy	Surface analysis technique which detects all elements.
TGA	Thermogravimetric Analysis	A measure of weight change related to temperature.
TMA	Thermomechanical Analysis	A measure of physical properties related to temperature.
XPS	X-ray Photoelectron Spectroscopy	Elemental analysis of surface layers.
XRD	X-ray Diffraction	Analysis of materials and crystal structures by X-ray impingement.
XRF	X-ray Fluorescence Spectroscopy	Bulk analysis of solids or liquids by X-ray excitation.

In addition to the fracture mode, electron microscopy can be used to identify types of mechanical damage, such as adhesive or abrasive wear, corrosion, and other distinct features. To some extent, surface roughness or machining quality can also be evaluated. Degradation products and inclusions can be examined via electron microscopy, and these minute features can be analyzed and identified by X-ray spectroscopy or other techniques within the microscope.

Special Testing

This group of tests available to the failure analyst includes all of the tests which do not easily fit into the previous categories. Many of these can be performed to obtain additional information about materials or about a material's failure. Many tests which would fall under special testing are newly developed and sophisticated tests which were not feasible prior to the advent of affordable computers and the development of suitable analytical software. The following are a few of the more important techniques:

Fracture Mechanics:

Fracture mechanics is a tool often used in failure analysis to approximate the stresses surrounding a fracture to better explain its occurrence. By making certain assumptions and isolating the fracture location, simulations of crack growth scenarios can be calculated. Alteration of the determined model parameters can estimate the magnitude of the mechanical stress applied to a component at the time of failure. This is often used in tandem with NDE measured flaw sizes to determine the reduced loads necessary to result in crack growth with a flaw of certain dimensions. Mechanical properties measured during destructive physical analysis can be used in this modeling to obtain more specific information.

Finite Element Analysis:

Finite Element Analysis, or FEA, is an advanced modeling technique which can be used to predict the location and magnitude of stresses on individual components within complex assemblies. This type of analysis also utilizes the computational capabilities of current technology. Changing the location and magnitude of simulated loads on the 3-dimensional model may indicate the reason for a failure. In some circumstances this type of engineering analysis is of utmost importance when physical evidence is not available but mechanical loading is known.

Simulation:

In some instances, sophisticated test beds and test apparatuses can be developed for approximating service conditions involved in a materials failure. Although this tool is more often used during product development, the ability to reproduce a failure is a very clear-cut proof of a failure hypothesis. By altering the physical simulation using specific parameters associated with the failure, an exemplar part similar to the failed one can be tested. Naturally, the actual factors contributing to a failure may be too numerous and varied to adequately simulate, however, materials failures where mechanical stresses are the only significant cause are not uncommon.

Part IV: Analyze Data and Prepare a Report

Conclusions:

After all of the systematic examination and data collection has been completed, the information must be organized and interpreted for its significance to the failure. The assembled results from the different tests must be considered collectively, as the final hypothesis needs to be in substantial agreement with all physical evidence and test results. As the investigation reaches its fruition, most of the possible failure causes can be conclusively discounted and a single, coherent explanation is indicated. At this stage of the investigation it pays to have kept an open mind throughout, as the results need not conform to preconceived notions or desired outcomes.

Presentation of the results in a technical report is a very essential portion of a failure analysis. The data should be arranged and organized in such a manner that the information proceeds from general to specific, similar to any professional technical report. The training and experience of the investigator are required to assemble the often large volume of information into a contiguous report which logically leads to the conclusions.

Recommended Corrective Action:

In many failure analyses the resolution of a single incident is subordinate to the desire to avoid similar failures in the future. A good investigation can provide specific recommendations concerning design, materials and processing changes which will avert identical failures to other existing products. One of the possible exceptions to this is in litigation, where determination of the specific failure cause is paramount and may supersede other interests.

Part V: Review Implemented Corrective Actions

Naturally, changing the properties of any component in a complex assemblage of parts can alter the forces on adjacent components, and these changes may not always be readily predicted. Prudent engineering evaluation of all recommended changes must be performed prior to implementation, as other, potentially more severe, failures may result.

Equation for a Successful Failure Analysis

Proper Background Information

+

Correct Analyses and Tests

+

Thorough Knowledge of Materials Behavior and Processing

+

Pertinent Experience

Correct Analysis

Failure Analysis Rules

(1) The failure investigator has only one objective – to determine the failure mechanism(s) that caused the failure and to use that knowledge to prevent another occurrence.

(2) Start with and maintain an open mind. Emotion obscures objectivity and must be expunged from the investigation.

(3) The theory, however elegant, must agree with the observed evidence, however humble.

(4) The simplest solution is the best solution.

(5) Having the wrong solution is frequently much worse than having no solution.

(6) Major incidents are often triggered by very minor or innocuous appearing details.

(7) There is only one thing worse than knowing you have a crack growing in a component, and that is not knowing you have a crack growing in a component.

(8) Cracks never get smaller, no do they ever disappear. Either they stay the same size (invariably in a minor, insignificant, or easily repaired component), or they get bigger (usually in a critical component).