ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY & ENVIRONMENT
AZOJETESeptember 2020. Vol. 16(3):587-604
Published by the Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria.
Print ISSN: 1596-2490, Electronic ISSN: 2545-5818
www.azojete.com.ng

ORIGINAL RESEARCH ARTICLE

AN OVERVIEW OF APPROACHES AND TECHNIQUES USED IN FAILURE ANALYSIS OF ENGINEERING SYSTEM

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ARTICLE INFORMATION

Submitted28 March, 2020
Revised 02 July, 2020
Accepted 10 July, 2020

Failure Calamity,
Costs,
Inevitability,
Analytical Principles,
Correct Information,
Recurrence Prevention

ABSTRACT

Failure of engineering system such as vehicle, building, aircraft, bridge, equipment, and industrial facility is often inevitable with calamitous consequence and/or much loss; and is highly detested. Inevitability of engineering system or component failure stems from factors such as unavoidable corrosion and wear and tear, abnormal service conditions, substandard maintenance practices, improper inspections, production errors, design errors, injudicious selection of materials, material imperfections, overloading and other service abuses of the system or component; and unknown causes. The importance and value of failure analysis in providing vital information for preventing recurrence of failure case of engineering system and the need to properly conduct the analysis has been found well documented in the literatures. Various standard approaches and techniques of engineering system failure analysis have been reviewed and presented together with 24 recent works of researchers from different backgrounds on the subject who have taken particular cases for study and evaluation. The review shows that although there are many existing failure analysis approaches and techniques of engineering systems, not all or a number of them can be suitable for every particular failure case. Critical analysis of the approaches and techniques shows that each has limitations or demerits in terms of practicability and/or cost-justification for particular failure cases. The notable issue in the review is the need to always select the best approaches and techniques for particular failure cases to assess characteristics that are present in the failed/damaged engineering system or item and those that are supposed to be present in it before failure, the differences between the damaged and undamaged system or item, and results of tests that must be performed to substantiate explanations and refine knowledge about the observed damage to correctly reveal the root cause/s of failure. Another important thing found from the review is the need to first and foremost preserve evidence of the failed system or item before using the best approaches and techniques to get as much as possible information from the field failure conditions and background realities and laboratory tests of the failed system or item. The review is posited as a readily available compendium of basic practicable information that is easy to read and understand; for consultation by concerned students, researchers, and practitioners who are not yet much experienced in failure analysis of engineering systems and need the information for furthering their knowledge on the subject.

1.0 Introduction

A component, machine, process, or system is considered to fail if it has deteriorated to the extent that it is unsafe or only marginally capable of performing its intended function (Guma et al., 2019). The consequences of failure can vary greatly from structure to structure, system to system, and equipment to equipment. Failures come in all shapes and sizes in forms such as individual part, entire machine or process, with various modes such as fracture, fatigue, corrosion and high-temperature mechanisms (Vander Voort, 1975., Aliya, 2002., ASM, 2015). The commonly attributed reasons for failures of engineering system or component include: environment-material interactions which is essentially corrosion and wear and tear, abnormal service or operating conditions, substandard maintenance and repair practices, improper testing or inspections, assembly or fabrication or manufacturing errors, design errors in stress conditions, injudicious material selection, incorrectly assumed material conditions or properties, material imperfections due to faulty processing or fabrication, overloading and other service abuses of the system or component; and unknown factors (Vander Voort, 1975., Aliya, 2002., Fernando, 2013., ASM, 2015). Engineering systems include vehicles, buildings, aircrafts, bridges, equipment, and industrial facilities with their component parts (Aliya, 2002., Fernando, 2013., Wooten, 2015). Mechanical failure of engineering system or component can be catastrophic with consequences that manifest in several forms such as fatalities, injuries or suffering from minor cuts and bruises to broken limbs, whiplash, back and spinal injuries, paralysis, financial and mental effects on personnel involved, emotional and mental distress as people can suffer from post-traumatic stress from being involved in the accident or from losing a loved one, damage of assets or properties, loss of functionality and environmental damage, need for minor or costly repairs, reduction of production or service efficiency, waste of valuable materials, increased costs, and property and economic losses (Vander Voort, 1975., Aliya, 2002., Fernando, 2013., ASM, 2015., Wooten, 2015). These consequences can be very enormous in some cases and are highly detested. It is therefore desirable that failures of critical engineering systems must be avoided in all ramifications or prevented from recurring where it unavoidably happens (Aliya, 2002., Fernando, 2013., ASM, 2015., Guma et al., 2019).

A crucial method of preventing recurrence of failures of engineering systems or components is through failure analysis (Vander Voort, 1975., Fernando, 2013., ASM, 2015). In failure analysis, detailed assessment is performed on failed items or components at macroscopic and microscopic levels to determine the reasons that clearly identify the root cause of the failure often with the main motive of recommending recurring preventative action/s (Janssens et al., 2011., ASM, 2015., Wooten, 2015., Guma et al., 2019). Although the main intentions in most failure analyses is to use the acquired information to prevent recurrence of the failure; failure analysis can also be done for product development to meet market demands or improvement to reduce warranty costs, and assignment of responsibility in case of litigations that arise from the failure due to reparation of financial losses and physical damage or bodily injury or death. Failure analysis can save money, lives, and resources if done correctly and acted upon. The importance and value of failure analysis to safety, reliability, performance improvement, and economy is well documented in the literatures (Vander Voort, 1975., Aliya, 2002., Fernando, 2013., ASM, 2015). Failure analysis is an important discipline in various industrial sectors such as components manufacturing, fabrication, transportation services, building services, and power supply (Vander Voort, 1975., Aliya, 2002., Fernando, 2013., ASM, 2015). In some cases of failure analysis, tests can be performed but no indication of tangible fault be found. Such cases indicate that the real conditions of the failure cannot be duplicated in laboratory conditions so the cause of the fault is undetermined (Russel and Jur, 2017., Lv et al., 2019). In such cases, there is either the problem of environmental uncertainty or human error that can't be detected in the original failure scenario. Suggestions for analyzing these types of failures involve applying more tests, contracting additional and different failure analysis, contracting services or increasing the available data set for analysis (Russel and Jur, 2017).

Because of the critical role of failure analysis, it is important that errors be avoided in the analysis because they could create as much or more harm than the original failure by causing economic, psychological, and political consequences to particular individuals or companies who are implicated for carelessness, negligence, simple ignorance, or other errors or omissions by information from the analysis. With these regards, many prospective analysts can consider failure analysis to be meticulous and incriminating with fear of overlooking important details, so refuse to perform the analysis unless given enough time and full financial support to do thorough investigation. Pitfalls of analysts can include jumping to conclusions, not understanding the problem, not understanding how the failed system is supposed to operate, not considering all possible failure causes, and tearing system apart without a developed plan (Aliya, 2002., ASM Handbook, 2002., Janssens et al., 2011., Wooten, 2014., ASM, 2015).

Aim

The aim in this paper is to review basic prevailing literatures on failure analysis of engineering systems or structural components and present a compendium of contemporary applicable approaches and techniques used in the analysis.

The review covers only basic existing standard approaches and techniques used in failure analysis of engineering systems and some case studies from different engineering backgrounds by practitioners in which some of the approaches and techniques were used. The benefits that can be derived from the review report are:

i. Provision of consolidated information for simpler reading and understanding and interest motivation of researchers, professionals, and students who are concerned with failure analysis of engineering systems but are not much experienced on the subject and need the information for advancing their knowledge on the subject.

ii. Provision of consolidated information that gives better insight into what is analytically achievable and not achievable in failure analyses of engineering systems with the existing approaches and techniques for the way forward by concerned researchers or analysts.

2.0 The Review Report

Information presented in the review was sourced from various literary sources as it concerns approaches and techniques used in failure analysis in engineering with attempt to integrate and present the information in a simpler way for reading and understanding, and motivation of interest in the area of failure analysis.

2.1 Approaches and Techniques Used in Failure Analysis

Failure analysis to obtain correct applicable information is a meticulous exercise that requires use of correct approaches and techniques. Failure analysis approaches are the itemized sequential ways of analytically dealing with a failure case while failure techniques and tools are the means of accomplishing the approaches. While there are generally many approaches and techniques in failure analysis, not all or the same given number of the approaches and techniques may be applicable to different failure cases. The failure analyst is therefore required to know the existing available approaches and techniques and be able to select the best that will help them to best analyze their various individual failure cases. The choice of available approaches and techniques used in failure analysis greatly depends on the type and size of system or item that fails, nature of the failure in terms of magnitude, the location where the failure occurs in the system or item, the environmental location where the system or item fails, the material make and fabrication of the component parts of the item, time required for the analysis, and the accuracy level required in the analysis (Aliya, 2002., ASM Handbook, 2015., Lv et al., 2018).

2.1.1 Approaches Used in Failure Analysis

The key principle in failure analysis is to first and foremost preserve evidence and get as much as possible information from the field conditions and develop a complete case history of the failed item or system. This requires getting information on the failed item in terms of manufacturing processing and service usage and maintenance level, including details of the failure before intelligently selecting tests and procedures that are best for supplementing the information in analysis of the failure (Aliya, 2002., Janssens et al., 2011., Wooten, 2014., ASM, 2015., Lv et al., 2018). Depending on the nature of the investigation, the approach steps involved can include all or various combinations of the following (Aliya, 2002., ASM, 2015):

i. Assembling background data. The information that the analyst presents must include; date and time of failure, name of the failed item or system, location where the failure occurs, how the failure occurred according to any eyewitness' or proven accounts, extent of damage and injuries and other losses from the failure. The information must also include; appearance, any identification numbers, owner, user, manufacturer and/or fabricator, function, service life at the time of failure, rating performance, operational levels, normal and abnormal loads, frequency of loading, environmental location, material makes, manufacturing and fabrication techniques, maintenance records, specifications and codes governing manufacturing and maintenance, inspection account, service operational temperature and pressure and speed ranges, strength and toughness levels, and any service deviations for the failed item or system. The fabrication procedures must include details of any welding, adhesive joining, coatings, bolting, riveting, heat treatment, and stress relief or other thermal processing in the failed item or system (Aliya, 2002., ASM Handbook, 2002., ASM, 2015).

ii. On-site visual examination and taking of photographs or drawing sketches of the failure area and adjacent areas to schematically record and gain important primary clues about the origin of failure, presence of stress concentrators, presence of any temper color or scale on fracture faces, orientation and magnitude of stresses, failure mode and mechanism, direction of crack propagation and sequence of failure, presence of contributing imperfections and corrosion and wear damages, sizes, and other physical data (Ghosh, 1997., Aliya, 2002).

iii. Field visual macroscopic examination of failure locations or with the aid of magnifying glasses or other means where visual observation is difficult for evaluation of surface homogeneity, integrity, and quality levels of the locations by comparison with the normal associated features or values for them (Colangelo, 1978., ASM Handbook, 2002., ASM, 2015)

iv. Field or laboratory analyses of temperature, pressure, wind speed, humidity, chemical contents, and levels of radiation and electric current presence in the environment in which the failed item or system operates to know whether there are significant deviations in values of these parameters from their standard range values for the environment or there are unusual inimical factors such as corrosion in the environment (Jones, 1993., Janssens et al., 2011).

v. Collection of test samples from critical locations such as the damaged and undamaged locations of the failed item or assembly (Aliya, 2002., Wooten, 2014., Russel and Jur, 2017).

vi. Conduction of fractography investigations and analyses to gain understanding of brittle or ductile, fatigue, creep, corrosion, and wear fracture mode behaviors of failed materials as well as relative attendant stress levels and orientation of the stresses and loads on the materials (Jones, 1993., Lv et al., 2018).

vii. Conduction of chemical, micro-structural, micro-hardness, and corrosion tests analyses of failed welded, soldered, and brazed joints in relationship to standards for them (Ghosh 1997).

viii. Performance of chemical analyses of all other failed materials including critical surface corrosion products, deposits or coatings by comparison of results with standards or established specifications for the materials (Colangelo, 1978., Janssens et al., 2011).

ix. Determination of mechanical properties of failed components by appropriate tests and comparing obtained values with standards or established specifications for the components (Aliya, 2002., ASM Handbook, 2002).

x. High-magnification metallographic examination of failed material sections using suitable microscopes to evaluate micro-structural surface features such as, crack paths, inherent defects, and corrosion attack sites in relation to known normal micro-structural phases of the material locations (Russel and Jur, 2017., Lv et al., 2018).

xi. Micro-hardness testing to measure case depths, and evaluate cold-worked parts that fail (Aliya, 2002., ASM, 2015).

xii. Micro-probing for any critical abnormalities, such as inclusions and segregations that are too small for bulk analysis (Russel and Jur, 2017).

xiii. Determination of residual stress levels and relative amounts of phases such as austenite or retained austenite, ferrite, delta ferrite or martensite, sigma, and carbides in critical structural materials like steels (Jones, 1993., Janssens et al., 2011).

xiv. Performance of simulation tests to evaluate critical material characteristics such as stress-corrosion cracking and fatigue tendency in particular environments to determine the degree of embrittlement or confirm the method of heat treatment or harden-ability (Ghosh 1997., Janssens et al., 2011., Russel and Jur, 2017).

xv. Summarizing and analyzing all pertinent data to identify the root cause of the problem (Jones, 1993., Lv et al., 2018).

xvi. Writing the report and distributing it with recommendations for preventing future failures or problems in similar existing item or system (Ghosh 1997., Wooten, 2014).

xvii. Following up on these recommendations (Aliya, 2002., ASM Handbook, 2002., ASM, 2015).

xviii. Preserving the evidence for the benefit of other examiners (Aliya, 2002).

2.1.1.1 Techniques Used in Failure Analysis Approaches

Failure analysis cannot be possible without a sound knowledge of various information-gathering or evaluation techniques and tools to achieve the itemized approaches. In cases where feasible, multi-technique evaluations can be applied to have higher confidence of the generated data by optimization (Wooten, 2014). The available and commonly used evaluation techniques and tools that can be used for various types and extents of failure analyses essentially include (Ewalds and Wanhill, 1984):

i. Photographic documentation of information on critical areas of failed items or systems using film or digital cameras (Aliya, 2002).

ii. Magnetic-particle inspection to locate surface and subsurface discontinuities in ferromagnetic materials (Ewalds and Wanhill, 1984., Walraven, 2003).

iii. Stereo-photography for documenting component conditions and recording information in three dimensions by using a stereo-camera or sequentially by the repositioning of a single camera (Ewalds and Wanhill, 1984., Karayan et al., 2012).

iv. Metallographic examination of sections and analyses to reveal any material imperfections such as micro-structural segregation, decarburization, carbon pickup, improper heat treatment, un-tempered white martensite, second phases such as γ' in nickel-base super-alloys and inter-granular corrosion using optical or electron microscopy (Ghosh. 1997., Walraven, 2003).

v. Surface preparation of metallographic samples using various methods such as grinding, polishing, and etching by various available means (Ewalds and Wanhill, 1984).

vi. Radiography using techniques such as x-rays, and gamma rays to locate internal cracks and other defects (Walraven, 2003).

vii. Molecular structure analysis by techniques such as differential scanning calorimetry, and molecular weight evaluation for evaluating levels of molecular weight deviations from values known for chemical substances (Walraven, 2003).

viii. Thermo-mechanical analysis, dynamic mechanical analysis, mechanical testing, and hardness analysis for evaluating physical properties using relevant test facilities (Ewalds and Wanhill, 1984., Walraven, 2003).

ix. Corrosion tests using simulated conditions to find any logical reason for the failure of system or item where normal investigation procedures on materials, manufacturing, and service related aspects has failed (Colangelo, 1978., Ghosh, 1997).

x. Macroscopic examination and analysis of fracture surfaces at lower magnification using suitable means such as unaided eye, hand lens or magnifying eye glasses, low-power stereoscopic microscope, and scanning electron microscope (SEM) for faster detection of defects and flaws that are not too small (Colangelo, 1978., Walraven, 2003).

xi. Eddy current inspection of material that conducts electricity to detect surface and subsurface cracks or flaws in the material (Walraven, 2003., Pantazopoulos, 2019).

xii. Microscopic examination of fracture surfaces to determine the origin(s), mode, and direction of propagation of very small cracks or fractures and other flaws using typically SEM but also other microscopes of various types and advantages such as atomic force microscope (AFM), scanning superconducting quantum interference device (SQUID) microscope, stereomicroscope, optical microscope, scanning acoustic microscope (SAM), USB microscope, photoemission electron microscope (PEM), X-ray microscope, and infra-red microscope (Walraven, 2003).

xiii. Residual stress analysis in the materials using typically x-ray diffraction technique (Ghosh, 1997., Pantazopoulos, 2019).

xiv. Finite element analysis (FEM) method in certain cases where a more comprehensive analysis is needed because a conventional failure analysis approach is not enough to reveal the failure cause (Ewalds and Wanhill, 1984., Karayan et al., 2012).

xv. Fracture mechanics analysis for theoretical investigation of failures such as fractography to establish whether or not the presence of discontinuities in material have contributed to the failure of the component under given service load conditions, as well as formulation of preventive measures (Pantazopoulos, 2019).

xvi. Preparation of very small samples for test analyses using means such as jet-etcher, plasma etcher, back-side thinning tools, mechanical back-side thinning, and laser chemical back-side etching (Bloch and Geitner, 1994., Walraven, 2003).

xvii. Spectroscopic analysis techniques such as transmission line pulse spectroscopy (TLPS), auger electron spectroscopy, deep-level transient spectroscopy (DLTS), and device modification such as focused ion beam etching (FIBE) for detecting defects in semiconductors, charge carriers, atoms, and molecules (Bloch and Geitner, 1994., Walraven, 2003).

xviii. Surface analyses for cracks and other discontinuities of non-magnetic materials using techniques such as dye and other liquid-penetrant inspections (Ewalds and Wanhill, 1984., Ghosh. 1997., Walraven, 2003).

xix. Electron microscopy to analyze extremely small defects in materials including microelectronic components by various methods such as electron beam induced current (EBIC) in scanning electron microscopy (SEM), SEM, charge-induced voltage alteration (CIVA) in SEM, energy-dispersive x-ray spectroscopy (EDS) in SEM, voltage contrast in SEM, electron backscatter diffraction (EBSD) in SEM, and transmission electron microscopy (TEM) (Bloch and Geitner, 1994., Walraven, 2003).

xx. Laser signal injection microscopy (LSIM) such as light-induced voltage alteration (LIVA), optical beam induced current (OBIC), laser-assisted device alteration (LADA), optical-beam-induced resistance change (OBIRCH), thermally induced voltage alteration (TIVA), external induced voltage alteration (XIVA), dynamic soft defect localization (DSDL); to locate defects or failures of transistors, semiconductors, and integrated circuits by scanning a laser beam through a microscope lens over an integrated circuit while monitoring the device current /voltage response for laser induced changes (Bloch and Geitner, 1994., Walraven, 2003).

xxi. Semiconductor probing such as laser voltage prober, time-resolved photon emission prober (TRPE), nano-probing, mechanical probe station, and electron beam prober for analysis of defects in semiconductors (Bloch and Geitner, 1994., Walraven, 2003).

xxii. Software-based fault location techniques such as CAD navigation, and automatic test pattern generation (ATPG) fabrication for detecting faults in circuit layout and performance (Bloch and Geitner, 1994., Walraven, 2003).

xxiii. Techniques for chemical characterization of materials, coatings, corrosion products, etc; by means such as energy-dispersive spectroscopy (EDS), wavelength-dispersive spectroscopy (WDS), Raman spectroscopy, atomic emission spectroscopy, Auger electron spectroscopy (AES), x-ray photoelectron spectroscopy (XPS), time-of-flight secondary ion mass spectrometry (TOF-SIMS), Fourier transform infrared spectroscopy (FTIR), and chromatography (Walraven, 2003., Wolfgong, 2016).

2.1.2 Reviews of some Analytical Rigors and Recent Developments in Failure Analyses by Researchers

For better appreciation of how the various approaches and available techniques or tools in failure analysis are exploited for different failure cases, the works of some practitioners or researches from different engineering disciplines on the subject who have taken particular cases for study and evaluation in the past few years have been reviewed and presented as follows:

Effect of isothermal ageing on two high temperature failures of 204°C and 250°C of bismaleimide composite materials, a novel CSIRO CBR 320/328 composite and a commercial CIBA GEIGY Matrimid 5292 composite was examined by Fox et al. (2004). They noted that de-lamination was a major cause of failure in composite materials. They therefore measured the Mode I inter-laminar fracture toughness of both materials using the double cantilever beam (DCB) test. They monitored chemical degradation of the matrix concurrently using Fourier transform infrared (FTIR) and Raman spectroscopy. They found chemical changes at the core of all these materials to occur concomitantly with the observed changes in inter-laminar fracture toughness. Their FTIR analysis of both matrix materials revealed the predominant degradation mechanism to be the oxidation of the methylene group bridging two aromatic rings common to the structure of both resins that was substantiated by in-growth of a broad peak centred at 1600/cm. In addition to this, they found the pyromellitic anhydride unit present only in the CBR 320/328 composites to be highly resistant to the effects of ageing, whereas the saturated bismaleimide, common to the cured structures of both materials was observed to degrade. Their Raman spectroscopy indicated that the predominant degradation mechanism of the composites differed at the two ageing temperatures (Fox et al., 2004).

Lee et al. (2004), analyzed the causes of the incident of a Cessna trainer whose propeller was separated due to the cracking of the propeller blade hub during the takeoff roll. They observed beach marks and fatigue striations, typical of fatigue cracks on the fracture surface and detected corrosive oxides in the center of beach marks that were considered to be the crack origin. They found that the stress acting on the fracture surface under corrosive environment formed corrosive oxides, such as mud cracks. By analyzing the fractography and metallography of the failed parts, they found that the propeller blade hub nucleated stress corrosion cracking (SCC) as a result of residual stress and corrosive environment and the SCC was the cause of the fatigue crack. Moreover, they found a fatigue crack to reach its critical length by repeated cyclic stress, which occurred during the rotation of the propeller blade and then, the rest of the fracture occurred instantaneously (Lee et al., 2004).

Kim et al. (2005), conducted analyses of three failed Air Interceptor Missile (AIM)-9 rocket motors of different types used at different times, in order to identify the root cause of cracks occurring in the wing attachment of the motors. Through visual inspection, they found that corrosion severity was in proportion to the failure rate in each crack surface. They carried out chemical analysis, microscopic examination, and residual stress determination on the crack surfaces to find out the cause of crack initiation and the mechanism of crack growth. They found that the crack origin was covered with mud cracks produced by an interaction of corrosion and stress, and the cracks were propagated along the grain boundary in the longitudinal direction. They also found that the corrosion-promoting factors were on the crack surface, and the tensile residual stress acted on the channel area of the rocket motor. As a result of the analyses, they concluded that the stress corrosion cracking occurred due to the interaction of corrosive environment and tensile residual stress which were latent in the rocket motor body (Kim et al., 2005).

Failure analysis of the turbine disc of an aero engine, installed in a certain type of aircraft was investigated by Witek (2006). From visual examination of the fractured surface, he observed beach marks typical of fatigue failure. He utilized a non-linear finite element method to determine the stress state of the disc/blade segment under operating conditions and performed computations with excessive rotational speed. He found high stress zones to occur at the region of the lower fir-tree slot, where the failure occurred. He devoted attention of this study to the mechanisms of damage of the turbine disc and also the critical high stress area (Witek, 2006).

Baadkar (2010), conducted a study on structural failure analysis of a semi-trailer using Finite Element Method. He centred his research on an ongoing trailer component failure problem at the STEELBRO New Zealand Ltd due to cracks. In his research he systematically approached the problem using ANSYS finite element analysis software. His approach involved investigation of the problem and structural analysis of the trailer subjected to two types of service conditions. He simulated the service conditions in ANSYS which involved CAD and finite element modelling of the trailer, and then the finite element model was validated experimentally by strain gauges and geometrically by ANSYS element shape checking capability. He found that the finite element model subjected to static structural analysis confirmed the crack locations and indicated the cause of the failure. His further fatigue analysis on one of the loading conditions revealed potential of the fatigue to cause failure at the crack locations. He finally, concluded his research with a proposal of revised component design to overcome the failure at the crack locations and recommendations for further analysis on the trailer (Baadkar, 2010).

A combined analytical and experimental approach was utilized to analyze failures of steel axles in a fleet of refrigeration semi-trailers equipped with dual rear axle air-ride suspensions by Kadlec et al., (2010). They used experimental data in combination with an analytical model to identify the cause of the axle failures, estimated time to failure, and evaluated the relative effectiveness of proposed design changes to minimize future axle failures. The centre-pieces of their program were finite element and fracture mechanics models of the axles. Their conducted experiments in support of the analytical models consisted of: field and laboratory inspection of failed axles to determine failure mode and the size of pre-existing flaws, full scale trailer road testing to determine the service load spectrum, fatigue tests on laboratory specimens to determine material properties, and full scale axle fatigue testing to calibrate and verify the ability of the analytical methods to predict axle lifetimes. They also evaluated empirically the effect of design and manufacturing process changes of the axles. Their focus was on the analytical models. They evaluated two potential solutions which involved an axle reinforcing jacket, and replacement of the original axle with a thicker walled axle. These analytical models were vital tools which determined that both of these solutions effectively extend axle lives so that they had adequate design margins (Kadlec et al, 2010).

Karayan et al. (2011), studied the failure of a seawater inlet pipe. They first characterized the failure by a small leak at approximately the 4-8 o'clock position. They depicted a schematic drawing of the inlet pipe showing the backing bar near the leak location as shown in Figure1. This backing bar was installed on the welded surface. Their visual examination of this failed pipe was as shown in Figure 2. In order to find out the root cause of failure, they performed a number of laboratory tests. Their test results showed that the failure was caused by cavitation, as evident by the presence of a crater-like surface near the backing bar shown in Figure 3. They observably found these localized craters seemingly unusual since they were only noticed near the backing bar. They then used finite element analysis as additional tool to determine why this was the case. They executed the finite element analysis based on the pipe dimension and actual fluid conditions such as velocity, pressure, temperature, and implicit parameters. Because there were no data for the initial height of the unwanted backing bar, they assumed that the initial height was the highest backing bar found on the specimen. Interestingly, the failure location predicted by their finite element analysis matched up with the actual evidence as shown in Figure 4. Their finite element analysis precisely showed that the failure could be located around the backing bar where the eddy zone was formed in this area. As can be seen from Figure 4, the leaks and crater-like surfaces found in the area near the backing bar were attributed to the formation of eddy zones in this area. The length of the eddy zone predicted the area that might suffer from a flow-induced attack. As a part of their conclusion they averred that when results obtained from laboratory tests cannot sometime explain why a failure occurs but evidence indicates the existence of a certain problem, finite element analysis is the only tool that can help a failure analyst find the root cause of the failure (Karayan et al., 2011).

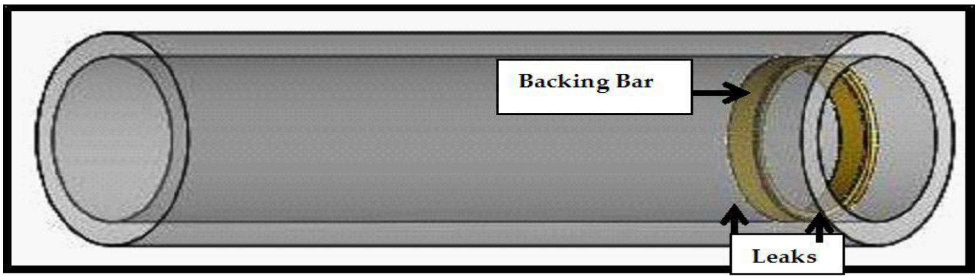

Figure 1: Big and small leak near the backing bar at about 6 o'clock position viewed from the inner side of seawater inlet pipe.

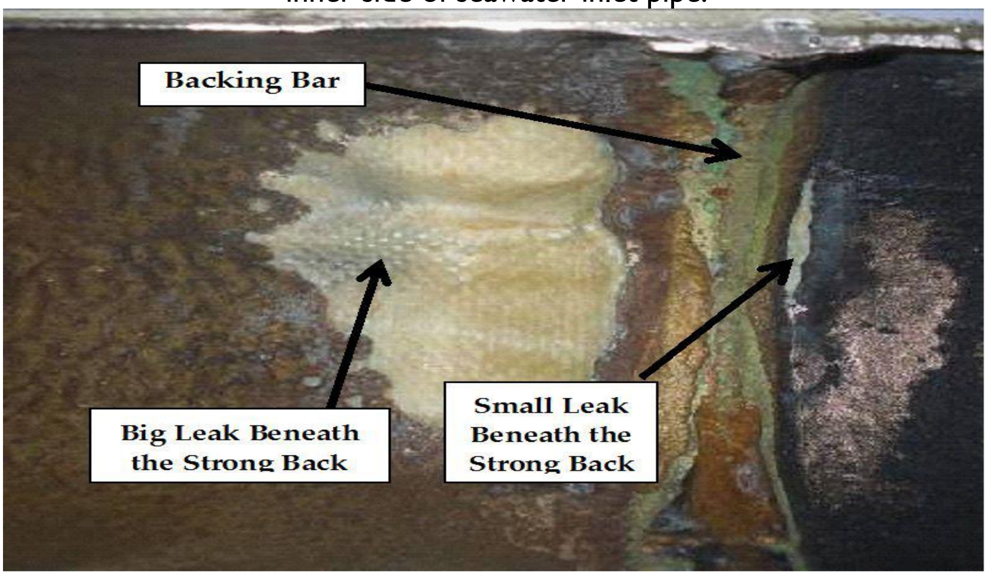

Figure 2: Big and small leak near the backing bar at about 6 o'clock position viewed from the inner side of seawater inlet pipe.

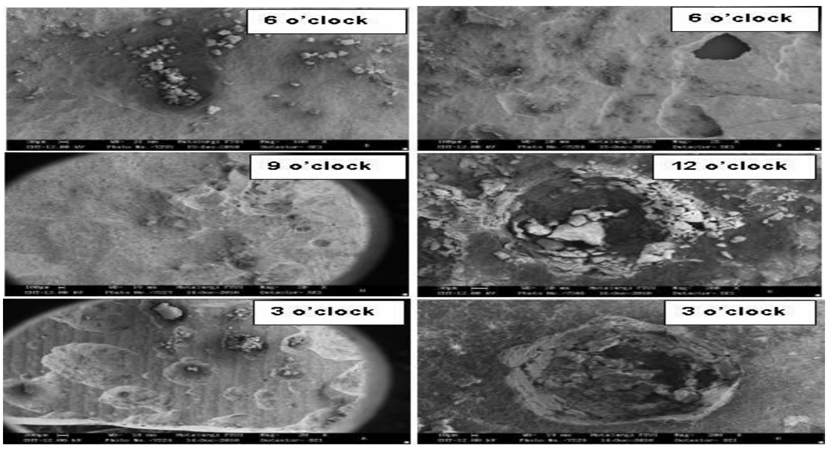

Figure 3: Surface morphologies of brown crater-like surface taken from 6-3 o'clock positions.

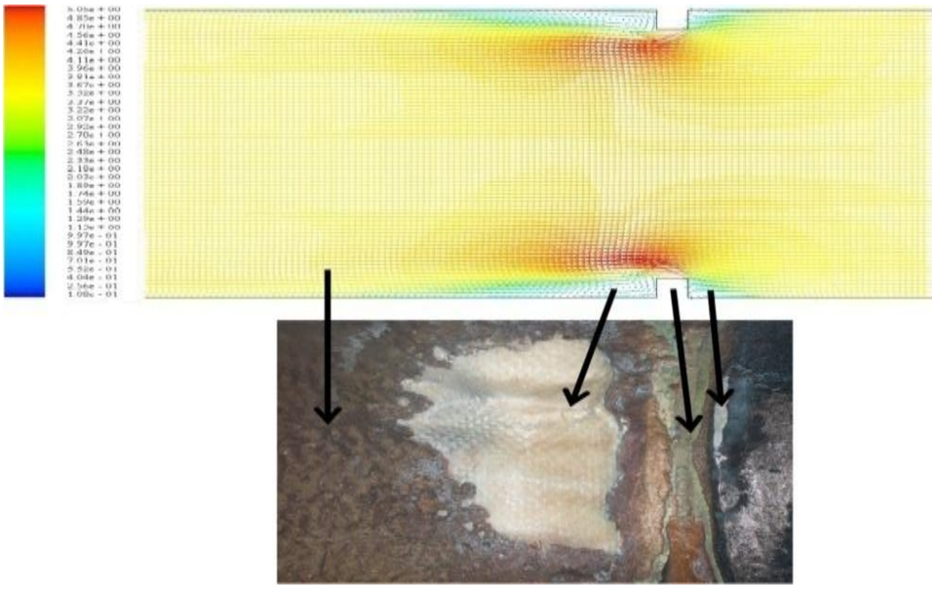

Figure 4: Finite element analysis of the inner pipe showing the orifice effect and the eddy zone near the backing bar correlated with the actual leaks on the inlet pipe.

According to Khare et al. (2012), most failures in the automotive systems depend on age and accumulated usage. They stated that typically, these criteria are covered under warranty for months-in-service (MIS), that is, MIS/age and a certain amount of usage (mileage) after the sales of the products. They pointed out that, warranty analysis of these systems enables manufacturers to understand field failures, and identify focus areas to make product improvements. They informed that typically, warranty analysis is performed based on MIS and moreover mileage is based on warranty analysis which has two added benefits, namely:

i. Some failures are by their physical nature, related to mileage rather than age. Hence, mileage is a better indicator for observing and quantifying these failures.

ii. Their observations also indicated that most vehicles leave warranty due to the mileage restrictions to the warranty coverage, rather than MIS.

In such a scenario, mileage-based warranty calculations can provide us with early information. Warranty analysis based on mileage has been presented in the literature as a supplement to the traditional MIS based analysis (Khare et al., 2012).

A case study of a catastrophic failure of a web marine crankshaft and failure analysis under bending and torsion applied to crankshafts were presented by Jadhav et al. (2013). Their microscopy and eye-seen observations showed that the crack initiation started on the fillet of the crankpin by rotary bending and propagated by a combination of cycle bending and steady torsion. The crack front profile approximately adopted a semi-elliptical shape with some distortion due to torsion. They supported the study by a previous research work already published by them. The number of cycles from crack initiation to final failure of the crankshaft was achieved by recording the main engine operation on board taking into account the beach marks left on the fatigue crack surface. Their calculated cycles by the linear fracture mechanics approaches showed that the propagation was fast which meant that the level of bending stress was relatively high when compared with total cycles of an engine in service. They however did not observe microstructure defects or inclusions which concluded that the failure was probably originated by an external cause and not due to an intrinsic latent defect. They also discussed possible effects of added torsional vibrations which induced stresses. They analyzed and reported some causes but the origin of the fatigue fracture was not clearly determined (Jadhav et al., 2013).

Nassef et al. (2016), investigated the failure of a rocker arm shaft of a passenger car. The shaft failed by brittle fracture across one of the four holes supporting the shaft into the cylinder head. The running distance of the engine just before failure was 40,626 km. Their visual examinations of etched sections of the failed shaft and a new one revealed four distinct zones of darker etching appearance. They found that these zones corresponded to the four locations where the rocker arms fitted the shaft. Their microscopic observations of the failed shaft revealed that the four dark-etching areas were surface hardened zones of martensitic microstructure. Furthermore, they found by scanning the microstructure along the failed shaft that heat treatment was so mistakenly extended by excessive heating so that the structure of the shaft near the supporting holes had considerable content of martensite phase. They confirmed this conclusion by their results of hardness measurements along the surface of the shaft. Microscopic investigations of the failed shaft revealed the presence of micro-cracks close to the supporting holes. They reasoned that these cracks might have been induced in the shaft by the non-uniform cooling during quenching in the course of heat treatment, or might have been nucleated by repeated loading during service. They finally concluded that this premature failure had occurred by the rapid crack propagation because of the lower fracture toughness of the martensite (Nassef et al., 2016).

A failure analysis investigation was performed by Rao and Eischen (2016), on a fractured heavy duty truck frame rail obtained during endurance track testing. They observed the fracture on the frame web within the torque rod connection to the rear drive axle of the vehicle. They found that this section of frame experienced multi-axial loading conditions including out-of-plane bending, twisting and shear under road loads. Their metallographic examination revealed micro-cracks on the edges of an open hole located in an area of high stress concentration. They saw this to be a manufacturing defect that acted as stress raiser and resulted in crack initiation. They conducted simulation of on frame rail using dynamic loads from a full vehicle model. After careful analyses of all their collected information, they concluded that the failure occurred due to an aggressively drilled open hole which created small crack initiations in a high stress-state location of the frame which resulted in extensive curvilinear crack growth under dynamic loads of the vehicle to fracture the frame rail (Rao and Eischen, 2016).

Due to frequent failures of coil springs on a specific type of motor vehicle, analysis of possible causes of failures was performed by Vukelica and Brcic (2016). They did the analysis on a single coil spring removed from a vehicle after failing in service. Besides their visual examination that revealed fracture on a first bottom coil, several other experimental techniques were used in the failure analysis. Using optical microscopy evaluation, they performed basic microstructure of the fractured surface and distinguished possible inclusions. They employed detailed scanning electron microscopy (SEM) examination at suitable magnifications to characterize the fine microstructure of the fractured surface and revealed flaws that served as crack initiation points. They used optical emission spectrometer with glow discharge source (GDS) sample stimulation to determine chemical composition of material used for the spring fabrication. Additionally, they performed hardness test. Using results of the performed experimental analysis, they recognized the possible causes of the failure. They reported that several factors, among them inherent material defect combined with material fatigue coupled with insufficient corrosion protection, caused failure of coil spring. They concluded that the obtained results were valuable in predicting behavior of coil springs mounted in other vehicles of the same type and could be taken as a reference in improving future design. They recommended further analysis including employment of finite element method to determine stress levels in undamaged and damaged coil spring along with numerical estimation of fatigue life (Vukelica and Brcic, 2016).

Bochnowski et al. (2019), investigated the failure of the belt conveyor made of 330 Nb heat-resistant steel working in a furnace for continuous heat treatment in a carburizing and oxidizing atmosphere. On the basis of microscopic tests and x-ray phase analysis, they determined changes in the microstructure in the cross-section of the conveyor wire after 731, 1642 and 2138 cycles of carburizing and oxidizing in the temperature range 30^{O}C to 850^{O}C in 160 minutes. Moreover, they carried out tensile tests to investigate the effect of the microstructure on the mechanical properties of heat-resistant steel. They found that the failure was due to a cross crack of wires of the conveyor belt mesh. Their results showed that on the surface of the alloy, Cr_2O_3 chromium oxides and $FeCr_2O_4$, $Mn_{1.5}Cr_{1.5}O_4$ oxides were formed. On the border of the alloy and chromium oxides, the airtight SiO_2 layer was created. They reported that as a result of the actions of external forces, transverse and longitudinal cracks were formed in the oxide layer. These cracks were the ways of carbon and oxygen diffusion. They additionally reported that in the oxidation and carburization process, degradation of the SiO_2 layer was promoted by the presence of Na, which was applied in washing agents used for cleaning products before placing them on the conveyor. They found that the microstructure of the unused wire of the conveyor belt consisted of G and H phases and NbC in austenitic matrix. Under the operating conditions of the conveyor belt, phase H dissolved in the matrix with the simultaneous increase of the G phase, and also the G phase was formed around the NbC carbides. High temperature carburizing led to the precipitation of massive carbides M23C6 with simultaneous significant depletion of chromium into an austenitic matrix to about 13%. Their quantitative micro-structural analysis showed that there was an increase in the size and participation of hard phases M23C6, G, NbC in the alloy microstructure. The volume fraction of precipitation increased from 3 to 24%vol. The resulting structure was characterized by low strength with significant decrease in ductility of the alloy (Bochnowski et al., 2019).

In his paper, Celvik (2019), summarized the work he conducted to assess the root cause of the failure of a medium commercial vehicle leaf spring that failed in service. He conducted macro- and micro-fractographic analyses by scanning electron microscope as well as material verification tests in order to understand the failure mechanisms and root cause of the failure. His findings from the fractographic analyses indicated that the failure mechanism was fatigue. He identified crack initiation to have occurred from a point on the top surface near to the front face and to the left side. He also observed two other crack initiation points that however did not propagate. The propagation mode of the fatigue crack revealed that the cyclic loads resulting in crack initiation and propagation were unidirectional bending. His fractographic analyses also showed that the root cause of the fatigue crack initiation and propagation was loading the part above design stress. He also verified material properties of the part by chemical composition analysis, micro-structural analysis, optical microscopy, and hardness tests (Celvik, 2019).

According to Roberts (2019), improper weight distribution can be a cause of structural failure in semi trailers. This can not only lead to the loss of the trailer, but also to the loss of cargo or even the possibility of an accident. He illustrated the following two case studies of losses caused by overloading semi-trailers. He depicted the view of a typical van trailer that sustained a sidewall failure in Figure 5 while carrying six pallets of copper wire, weighing approximately 3,178kg each.

Figure 5: A typical van trailer

He reported that the total load of 19,047kg in the trailer was unacceptable, according to the trailer manufacturer's load limit. The trailer manufacturer stipulated that a maximum concentrated load of 6,810kg in 3.048m of trailer length should not be exceeded (Roberts, 2019).

Guma et al. (2019), noted that failures of heavy-duty vehicles during load hauling are major concern in road transportation due to the magnitudes of accidents that sometimes result from the failures with loss of lives, destruction of goods or spillage with treat to environment, and road blockages. They averred that the failures are particularly detestable to the vehicle owners owing to the much loss they can incur including litigations they can face and compensations they can be obliged to make to affected innocent victims. They conducted analysis of shell failure of a semi-trailer tanker owned by an oil marketing company in Nigeria which resulted in much loss of the trailer's full-tank carried oil. The aim of their analysis was to provide information that could be useful for forestalling recurrent failure problems with the company's fleet of semi-trailers which had caused the company substantial losses in its annals. They first visually examined the as-failed shell to assess the nature and magnitude of the failure and documented information on where and how the failure occurred. They also surveyed and documented critical information about the trailer such as its maintenance record, usage level, competence level of its driver, mileage record, loading capacity, operational level, and collected samples from critical locations of the failed shell. Thereto, they conducted laboratory test analysis of the collected samples with respect to chemical composition, metallographic structure, and corrosion behaviors. By their visual inspections, they observed that the shell failed by a small brittle crack perforation along the seam of a previous weld repair. Reportedly; their collected background information showed no clear standard maintenance records of the semi-trailer, their chemical analysis showed a steel material of different composition at the failure location compared to the as-made shell carbon steel, their metallographic analyses showed that the failure location was heterogeneous compared to the as-made shell steel. Their corrosion analyses showed greater corrosion rates at the failure location which presumably raised the location stresses amid dynamic effects from bad road conditions and caused the shell to crack-perforate along the weld seam of the location (Guma et al., 2019).

Guo et al. (2019), evaluated micro-structural degradation in a failed gas turbine blade due to overheating. They reported that gas turbine blades may undergo overheating, which could cause serious micro-structural degradation and even failure of turbine components. Nonetheless, they noted that limited published investigations focus on the evaluation of the micro-structural degradation in overheated turbine blades. In their study, they investigated a high-pressure turbine blade, which comprised of equiaxed-cast super-alloy substrate and an Al-Si coating. They reported that the blade failed due to material loss at the airfoil tip of the leading edge. They conducted a systematic micro-structural investigation of the failed blade, and compared their results with those of thermally exposed samples. By taking several micro-structural degradation parameters as references, they evaluated the micro-structural degradation of the failed blade and estimated the equivalent maximum service temperature. Their results reportedly indicated that most locations of the failed blade had been operating under normal conditions; however, the airfoil tip of the leading edge had suffered serious overheating, and the overheating temperature was almost 200°C above the normal service temperature. The overheating led to incipient melting of the substrate and material loss of the service blade resulting in the failure (Guo et al., 2019).

Jiang et al. (2019), conducted analysis of failure initiation in corroded cast iron pipes under cyclic loading due to formation of through-wall cracks. They identified corrosion and internal water pressure as major factors contributing for the longitudinal failures in large-diameter cast iron water pipes. They reported evidence of deteriorating pipeline integrity due to fluctuations of internal pressure loading. They aimed their study to investigate the fatigue resistance of cast iron pipes and to identify the pipes in a water network that were at high risks of fatigue damage. They conducted stress-controlled fatigue tests on coupons prepared from exhumed cast iron pipes. They developed a correlation between tensile fatigue stress and cycles to failure based on experimental results. They proposed a methodology to identify critical factors for initiating a through-wall crack in cast iron water pipe considering the impact of fatigue. They conducted a sensitivity analysis with relevant factors, and the relative impact of those factors to cause a premature failure was assessed. They identified the operating pressures and stress ratios caused by pressure transients and long-term soil corrosion rate as the key contributing factors for severe fatigue damage (Jiang et al., 2019).

Katinic et al. (2019), described the failure of a rotor of a condensing industrial steam turbine installed in a fertilizer production plant. They identified a fracture of the two adjacent rotor blades in their roots. They carried out an analysis of the failure cause by the analyses; of the fracture location on the steam flow path, the corrosion deposits, and the modal of the rotor blades. They performed the modal analysis using the finite element method. They conclusively reported that the blades' failure was due to a phenomenon known as corrosion fatigue. To extend the useful fatigue life of rotor blades in the future, they redesigned the entire turbine stage of broken blades. They found that the modified design of the turbine stage increased the fatigue safety factor by about 50% compared to the original design (Katinic et al., 2019).

Khadem and Yareiee (2019), conducted research aimed to assess failure analysis of a boiler tube of a steam generation system at a petrochemical plant. To achieve this goal, they first made visual observation and took thickness measurements to detect different features of the failure. Thereto, they used optical microscope and scanning electron microscope (SEM) to observe the microstructures and also carried out hardness measurements for metallurgical evaluation. They also studied phase composition of deposits of the tube by using x-ray diffraction (XRD), and took into consideration the on-site water composition of the boiler. They finally performed Finite Element Analysis (FEA) to model the condition of the tube before failure. Based on the results of their analyses, they recognized "short-term overheating" as the root cause of the boiler tube failure (Khadem and Yareiee, 2019).

Lachowicz (2019), conducted studies on the inter-granular corrosion-fatigue failure of the Zn-Al alloy solenoid valve. The purpose of his performed studies was to determine causes of the solenoid valve corrosion which appeared during its operation. As a result of his performed macroscopic observations, he found that the cause of the valve corrosion was its unsealing. He reported that the unsealing led to strong corrosion of the solenoid valve body from its internal surface in the vicinity of the seat as a result of actions of surrounding chloride ions. This he said caused surface covering of the valve with white corrosion products characteristic for zinc alloys. He also reported that the resulting corrosion was of the inter-granular nature and propagated over grain boundaries and the inter-dendritic areas which led to decrease in the active cross-section of the valve and abnormal stress concentration that caused the valve failure (Lachowicz, 2019).

Liu et al. (2019), conducted fracture failure analysis and research on drive shaft of positive displacement motor. They investigated microstructures and mechanical properties of the fractured drive shaft by visual inspection, metallographic analysis, scanning electron microscopy, and tensile and impact tests. They tested the composition, structure and mechanical properties of the drive shaft materials in meeting the standards. They found that the fracture surface was mainly characterized by dimples and small amount of quasi-cleavage by microscopic analysis, which indicated that the fracture surface was dominated by ductile fracture. They also found through EDS spectrum analysis that at the bottom of the sample pit, there were a large number of grey inclusions which were turned to be iron oxides. They asserted that the existence of a large number of iron oxide inclusions in the metal would inevitably have serious impact on the performance of the drive shaft. They also conducted finite element analysis of the failure. The analysis showed that the stress on the cylindrical surface of the external thread near the shoulder would gradually increase greatly and the rupture risk would increase with the increase of torque and that it would also fail due to the relatively high stress on the root of the first tooth of thread. They found that the maximum stress near the thread shoulder was close to the yield limit of the shaft material when the borehole curvature was larger, and the bending load would lead to stress concentration on the optical axis section at the shoulder to affect safety of the drive shaft. Because there were a large number of inclusions in raw materials and the conditions in the well were complex, the carrying capacity of the drive shaft decreased and fracture of the shaft was finally caused. They found through comparative analysis that, the maximum stress value of the improved drive shaft was lower than that before the improvement. Their analyses showed that the safety factor and service life of the drive shaft could be improved by improved design (Liu et al., 2019).

Ni et al. (2019), carried out failure analysis on abnormal perforation of super large diameter buried gas pipeline nearby Metro Company in the United Kingdom. They noted that as a part of urban pipeline network, buried gas pipelines are mainly used to transport high-pressure natural gas, artificial gas, and liquefied petroleum gas. They pointed out that since such pipelines are exposed to various unpredictable harsh service conditions; it is easy for them to encounter failures. In their paper, they systematically investigated an abnormal perforation failure of super large diameter buried gas pipeline with an outside diameter of over 1000mm. They found that the failed pipeline had transported water gas before transporting natural gas and was welded with iron buttresses which were not treated by anticorrosive insulation treatment. Their further obtained results indicated that the accumulation of impurities from water gas caused localized corrosion on the lower surface of the inner wall of the pipeline which led to formation of corrosion pits. They also reported that thereto, stray current came from the Metro Company flowed into the pipeline through iron buttresses and brought about stray current corrosion inside the corrosion pits on the lower surface of the inner wall of the pipeline. In totality they reported that the compound effect of these two corrosions resulted in the corrosion perforations. They finally proposed countermeasures to address corresponding problems (Ni et al., 2019).

A comprehensive fault diagnosis method was developed by Yu et al. (2019), to analyze the failure of a multi-disc clutch. They developed the mechanical buckling model to investigate the relationship between the resistance torque and the periodic circumferential bright spots. They obtained the contact pressure and temperature on the friction surfaces with consideration of the concentrated reactive load of the C-clip. They explored the friction and wear characteristics of the friction disc under different temperature conditions by the pin-on-disc test, and then observed the surface morphologies of tested discs by the metalloscope. Their results demonstrated that both the thermal buckling and the mechanical buckling could result in the mechanical-thermal buckling. They reported that as the temperature varied from 15^{O}C to 400^{O}C, the disc experienced the abrasive wear, ploughing wear, adhesive wear and de-lamination wear in that order. They finally proposed the mechanical-thermal safety boundaries, and provided some suggestions for better design of the clutch. They recommended that; the C-clip should be optimized to avoid stress concentration, the teeth number of separate plates should be increased to improve the torque transmission capacity, and the thickness of separate plates should be different and determinable by their axial positions in the clutch pack (Yu et al., 2019).

3.0 Conclusion

An overview of approaches and techniques used in failure analysis of engineering system has been conducted. It is seen that the general causes of failure and the behavior of materials may be known, prevention of failure of an engineering system is difficult to guarantee in our technological world. Failure of engineering system or component can be calamitous with enormous losses and is highly detested. Failure analysis is the current technology through which recurrence of unavoidable failure cases can be prevented in engineering. The critical requirement in failure analysis is that, it must be correctly conducted to provide all necessary information that give substance to explanations for the root cause of the failure. There are various approaches and techniques from the literatures that are used in failure analysis of engineering systems but not all or a number of them can be suitable for every particular failure case. The critical issues in the review is the necessity for the analyst to first and foremost preserve evidence and get as much as possible information from the field failure conditions and background realities of the failed system or item. Other notable issue in the review is the necessity to select the best approaches and techniques to assess: characteristics that are present in the failed/damaged system or item and those that are supposed to be present in it before failure, the differences between the damaged and undamaged system or item, and results of the tests that must be performed to substantiate explanations and refine knowledge about the observed damage to correctly reveal the root cause/s of failure. The failure analyst is therefore supposed to have a sound broad knowledge of the approaches and techniques and be able to always select the best approaches and techniques that will enable correct analysis of individual failure cases. The reviewed basic prevailing standard approaches and techniques of engineering system failure analysis from various literary sources have been presented together with 24 works of researchers from different backgrounds on the subject who have taken particular cases for study and evaluation. The paper is intended to provide a compendium of contemporary practicable approaches and techniques used in failure analysis for motivation, better knowledge, and application interest of concerned practitioners and researchers that are not yet much experienced in the field. For high accuracy in failure analyses of critical failure cases, it is advisable where applicable to always conduct each case analysis using at least three-technique evaluations for cross-checking and optimization of results to have higher confidence of the generated information.

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