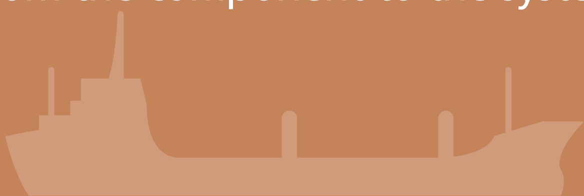
Lloyd's Register Foundation

Foresight review of structural integrity and systems performance

Ensuring safety from the component to the system



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About the Lloyd's Register Foundation

Our vision

Our vision is to be known worldwide as a leading supporter of engineering-related research, training and education, which makes a real difference in improving the safety of the critical infrastructure on which modern society relies. In support of this, we promote scientific excellence and act as a catalyst working with others to achieve maximum impact.

The Lloyd's Register Foundation charitable mission

- To secure for the benefit of the community high technical standards of design, manufacture, construction, maintenance, operation and performance for the purpose of enhancing the safety of life and property at sea, on land and in the air.
- The advancement of public education including within the transportation industries and any other engineering and technological disciplines.

About the Lloyd's Register Foundation Report Series

The aim of this Report Series is to openly disseminate information about the work that is being supported by the Lloyd's Register Foundation. It is hoped that these reports will provide insights for the research community and also inform wider debate in society about the engineering safety-related challenges being investigated by the Foundation.

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Executive summary

Modern society depends on complex products and engineering systems whose failure can lead to catastrophic consequences. The performance of these systems and the components within them is of prime importance.

The safety of systems is dependent on a hierarchy incorporating the integrity of individual components; assemblies of components that combine into structures, equipment and systems; operating and safety procedures; and the individuals that support the operation of the asset. At the core of assessing systems performance is the desire to make systems as safe, functional and reliable as possible.

This review aims to identify the key safety challenges that exist in structural integrity and systems performance where the Lloyd's Register Foundation can make a distinguishable difference by targeting its resources. To find these challenges we brought together a group of international experts, and openly consulted with the community to understand how different industries approach structural integrity and systems performance; what are the barriers to improvements in these industries; how these barriers can be overcome; and finally recommendations of the opportunities to make the greatest impact on the safety of the community. It concludes that structural integrity and systems performance advances can reduce the risks associated with operation and maintenance of assets, and the number of casualties associated with their failure.

This review has highlighted five themes that are common across industries and have the potential to improve safety.

Materials and their degradation

Understanding new materials and new methods of manufacturing and how to join them pose challenges to their deployment unless their long term performance can be understood and taken into account during design and operation. In many cases there is little or no experience of how new materials behave over the long periods associated with operation. In-service removal and testing of the materials may not be possible if an asset is to continue operating.

Measurement and sensing

To be able to understand the condition of an asset we must be able to measure or sense its condition. A lack of information about the current condition of an asset results in the need for conservative assumptions that can affect future availability and efficiency. Methods of measuring and sensing have been, and continue to be, developed and have the ability to provide vast amounts of data. The collection and analysis of data ranging from individual systems through to global arrays of systems will create unprecedented opportunities for predicting future condition and optimising reliability.

Simulation and modelling

It is possible to design assets following existing standards and best practices, but this can result in designs that are extremely conservative in nature. With better fundamental understanding of the processes that occur, combined with advances in computing power, it will be possible to better simulate and model how assets will perform in their operating environments.

Systems, complexity and risk

Assuring that a system will safely maintain its function lies at the centre of systems performance. Understanding both the functions that the asset must maintain and the risks associated with failures within one or more of its systems are essential. The complexity of systems is increasing which can lead to poor understanding of the consequences of a part failing. Reducing complexity and the number of points of potential failure can result in safer and more reliable systems.

Knowledge transfer

Knowledge transfer can relate to many things. Within this review it has been reduced to three key areas: knowledge transfer between industrial sectors; knowledge transfer between generations; and knowledge transfer to plug the skills gap in engineering.

The fundamental physical and mechanical principles that apply to assets are the same, yet different industries have developed different ways of doing essentially the same thing but with different outcomes. There already exist opportunities to transfer best practice across industries but this does not always happen for various reasons: understanding these reasons can lead to solutions that improve safety. A different aspect of knowledge transfer is that the engineering workforce is getting older and experienced individuals are not being replaced in sufficient numbers, or when they are replaced it is with people with significantly less experience. The creation of a way to capture practical knowledge that is not possible in the university setting would be of benefit to the community.

This review concludes with five recommendations to the Lloyd's Register Foundation for where it should consider focusing its resources. These can be summarised as:

- the safety of systems containing 3D and 4D additive manufactured parts
- engineering science challenges: advancing the state-of-the-art to maximise safety
- development of an economic whole-system approach to demonstrate safety and integrity
- data-centric engineering
- minimising the risks associated with maintenance and inspection.

Foreword

What is it that makes structural integrity and systems performance a critical factor in the design of any engineering product in the 21st century?

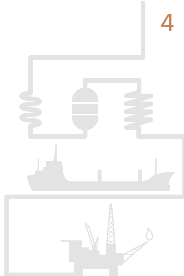
Structural integrity is a phrase that has gradually entered the public consciousness as a measure of the 'health' of a structure. In reality, in engineering practice, structural integrity can never be boiled down to a single number. It is a wide-ranging discipline that encompasses different approaches in different industrial sectors, but in all cases is trying to prevent failures.

In 1983 a bridge carrying Interstate 95 over the Mianus River in Connecticut suffered a failure when a portion of the deck collapsed into the river below, causing three fatalities. The direct cause of the accident was the corrosion of the hanger assemblies supporting the deck. The hangers were indeed difficult to inspect and maintain, but the root cause of the accident was traced back to a decision 10 years earlier to block and cover the main drains on the bridge, in order to reduce the maintenance cost associated with cleaning them periodically.

An equally important factor was that the design of the bridge was not fail-safe. The failure of one hanger assembly led to the collapse of the deck and there was no redundancy in the structure.

This is a prime example of a systems failure: while the actual failure event on the day of the accident was the result of corrosion, previous flaws in the design and maintenance processes were the principal causes.

Press Association Images



Systems performance casts its net more widely, encompassing the behaviour and operation of everything within a 'system', which may be a large structure such as a ship, aeroplane or oil platform, or a more diffuse system such as a transport network, or the civil infrastructure supporting a city. Systems performance includes aspects such as the structure, equipment, training, human reliability, human-machine interfaces, software, safe operating procedures, and business management systems.

Structural integrity is concerned with designing and operating products that are safe, incorporating a thorough and complete understanding of the loading and the environment they will encounter, underpinned by complete knowledge of the mechanisms by which the materials concerned will fail if their limits are exceeded. Structural integrity is a fundamental part of the overall concept of product performance, reliability and quality. It focuses on the performance of a physical part or component within a system.

Structural integrity is effectively a subset of systems performance, focusing more on the component or structure than the whole system. Both are concerned with optimisation of performance with minimal risk and maximum safety. There are common features to both of these disciplines, hence their alignment in this foresight exercise. Both require attention at the design phase; both require explicit attention to maintenance; and both require an understanding of the mechanisms and consequences of failure.

A particular aspect of systems performance is a realisation that the failure of an individual component, while it may be identified and comprehended and even mitigated, may be indicative of a broader failure within the system, such as an unintended consequence of changes to another part of the structure, a late design change, or a change to a maintenance schedule.

This report was commissioned by the Foundation to identify current best practice, technology trends and research needs in the domains of structural integrity and systems performance with the aim of identifying how we can enhance safety by fundamentally changing the design, manufacturing, maintenance and reliability of complex infrastructures from the component to the system. As the Lloyd's Register Foundation we do this, because life matters.

Professor Michael Fitzpatrick
Executive Dean, Faculty of Engineering and Computing
Coventry University

Professor Richard Clegg
Managing Director
Lloyd's Register Foundation

Background

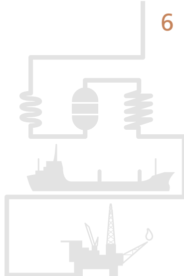
This review has been commissioned by the Lloyd's Register Foundation to identify research challenges in structural integrity and systems performance that can have significant future impact on the safety of life and property.

The Lloyd's Register Foundation is a UK registered charity and owner of the Lloyd's Register Group Limited, a 255-year old professional services company providing independent assurance and expert advice to companies operating high-risk, capitally-intensive assets in the energy and transportation sectors. This includes ships, oil rigs, power plants, and industrial facilities.

The review was informed and developed by an international team of experts, who met in London and Singapore in June 2015.

Building on the findings of this review, the Foundation will look to identify aspects of structural integrity and systems performance that might provide opportunities or threats to safety in line with its charitable objectives, and where the Foundation might focus its research and other grant giving to make a distinctive positive impact.

This review has been commissioned to identify research challenges in structural integrity and systems performance that can have significant future impact on the safety of life and property



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Introduction

All engineering industry takes an approach to designing products and systems such that they will safely meet a stated design life. This is true for products as diverse as light bulbs, aircraft, batteries, and oil rigs. Any individual product can often be treated as a 'system' in its own right. Abstract systems such as transport systems, or a road network within a transport system, will not be viewed as having a fixed life, but rather will be maintained and will evolve in response to changing demands.

Significant differences in approach exist between products, systems and sectors. The design principles for an aircraft, for example, are very different from a car, even though safety is a primary factor for each. The car has a greater focus on occupant protection during a crash, while for the aircraft the overall integrity of the structure over many thousands of flight cycles is paramount. Another example is that a skyscraper built in a region that experiences regular earth tremors will require different design and mitigation strategies than one built in a region that is geologically stable.

The ability to measure, compare and contrast the performance of complete systems – be that from a safety perspective, an environmental perspective, or a commercial perspective – is difficult and often not practicable when considering complex systems which depend on the interactions of structures, machinery and equipment, computer software, procedures and people. The concept of ‘risk’ is often invoked as a means to assess the acceptability of a particular system in terms of its performance against defined failure criteria.

Typically, the term ‘**risk**’ is defined as a combination of the following:

(a) the probability or likelihood of occurrence of an accident or event **X** (b) the resulting consequences in terms of human injuries, environmental damage and loss of property or financial exposure.

The more severe the consequences, the lower will be the acceptable likelihood of its occurrence.

The resulting consequences of an accident or event are sometimes referred to as the hazard. Wherever there are potential hazards, a risk always exists. To minimise risk, one may either attempt to reduce the likelihood of occurrence of the undesirable events; or contain, reduce or mitigate the consequences; or both.

Part of systems performance is the assessment, management and control of risk so that it remains below a tolerable level. Risk management and control should be an on-going process throughout the lifecycle of a system, from feasibility studies, through concept or front-end design, to detailed design, operation, and decommissioning. The different stages of the lifecycle will offer different opportunities and challenges for risk management and control.

In this report we have given preference to integrity and performance issues in industry sectors where there are severe consequences of failure, rather than, for example, failures of domestic appliances that are widespread but generally not life-threatening.

At the component level, about 80% of mechanical failures are somehow related to fatigue, alongside other mechanisms such as creep failure, wear or corrosion (see glossary on the next page). Failures of a product during manufacturing, fabrication or when the product is in service can result in injuries, downtime (reducing availability), repair, rework, scrap, recalls, lost output and liability claims; and constitute a significant part of costs for a manufacturer. A lack of understanding of the variability in manufacturing, assembly processes, and operational conditions are the major contributors to poor product quality and reliability.

Fatigue is a process of gradual initiation and growth of cracks in a material, as a consequence of oscillating loading. The loads involved will be typically well within the expected capacity of the material: it is the variation in the loading that drives the failure mechanism.

Creep is the gradual deformation of a material over time leading to failure, usually at high temperature. The controlling factor is how close the material is to its melting temperature, so polymer materials and low-melting-point metals, like lead, can creep at room temperature.

Wear is the progressive removal of material by an abrasive or erosive process.

Corrosion is most often evidenced in the form of rusting or pitting of iron or steel: a chemical reaction that reduces the amount of material present and enhances mechanical damage mechanisms (such as in stress corrosion cracking, or corrosion fatigue).

Design principles

The three basic design principles that are applied in structural integrity and systems performance are safe life, damage tolerance, and fail-safety.

Safe-life design assures the life of a component in one of two ways: either the loading and the environment that the component experiences are such that it will never fail (as long as the design limits are not exceeded, and the material's behaviour is fully understood); or the component has a fixed replacement period that is defined to ensure that it is removed from service before the known failure lifetime. An example of the latter category is the polymer timing belt used in petrol-engined cars which will eventually fail and must be replaced before this happens.

Another example of safe-life design is in the pressure vessel of several designs of nuclear power plant. Over the plant lifetime, irradiation effects cause gradual changes in the toughness of the steel, particularly at lower temperatures: and once the toughness has dropped to a certain level the plant must be retired.

Damage-tolerant design of a structure or component is intended to ensure that should some form of degradation occur during the operational life – typically by fatigue cracking, but also from corrosion or accidental damage – then the remaining structure can withstand expected loads without failure until the damage is detected. A key element of damage-tolerant design is that the structure is regularly inspected so that the extent of damage development can be assessed and repairs can be made – or the structure must be retired. There is also an implicit assumption that damage will occur during the product's life, and in some cases the assumption that the product contains flaws from the day that it goes into service.

Although nowadays damage-tolerant design is used for many safety-critical structures and components it was first developed by the aircraft industry. Taking metal fatigue of aircraft as an example, the principle is that the initiation and growth of fatigue cracks somewhere in an aircraft structure during its operational life is inevitable. The important thing is to ensure that a growing crack is detected, and if necessary repaired, before it becomes long enough to threaten the safety of the aircraft.

There are various design features which help attain a damage-tolerant structure. While the choice of material is important, there are both structural and systems tools that also come into play. One example is the use of multiple-load-path construction, where structural loads are spread over several members. Another is the use of crack stoppers, which can be as simple as the edge of a riveted plate that will prevent a crack in one plate from growing into another plate. However, riveted sections are inefficient in terms of weight, and so manufacturing technologies are moving towards integral one-piece structures. In order to ensure the same level of damage-tolerance, novel concepts such as bonded crack retarders are being developed. These are local stiffening straps that are affixed to the interior of a wing section that will slow a growing crack.

In order for damage-tolerant design to be effective, the overall systems performance becomes important. In an aircraft, the effectiveness of damage-tolerant design is entirely reliant on the ability to detect a growing crack, and knowledge of where are the critical locations that cracks can be expected. Modern aircraft are too large and too complex to inspect every square centimetre, so we must understand how and where damage will occur. The critical locations are determined in two principal ways: theoretical analysis of the structure; and the results of full scale fatigue testing of the aircraft (or a sub-assembly) that mimics the loads experienced during take-off, flight and landing.

Finally, **fail-safe design** looks to ensure that a structure or system contains some redundancy, so that a failure of an individual element does not lead to the failure of the structure or system as a whole. This may be achieved through having multiple load-bearing components; duplicated or back-up systems; or a defence-in-depth approach such as is employed in the nuclear power industry, where there are multiple systems and mechanisms in place in the event of a cooling failure (and which was breached at Fukushima through the failure of the back-up pumps). Such designs, which maintain minimum function under all conditions, are also known as resilient systems.

ALARA v. ALARP

One important difference that was uncovered by the workshops was whether the approach to risk minimisation in a particular industrial sector is as low as reasonably achievable (ALARA) compared to as low as reasonably practicable (ALARP). In essence, the ALARA approach means that all possible steps should be taken to minimise the risk of an adverse event. Cost may not be an issue, and if the risk cannot be effectively mitigated, then the activity – which may be the operation of a particular plant or product – may never be approved. The ALARP approach is different in that the risks concerned may be tolerated provided that it can be shown that the financial costs and effort required to reduce the risks further is out of proportion to the benefits gained.

The table overleaf attempts to show the differences that exist between different industrial sectors in the application of ALARA and ALARP.

Table 1
Approach to structural integrity and level of acceptable risk by industry sector

Industry	Approach to structural integrity	Level of acceptable risk
Aerospace	Aircraft structures design against fatigue using safe-life principles, but must prove damage-tolerance to the satisfaction of the regulatory authority. Structures are normally fatigue-limited, and an assumption is made of widespread defects in the structure (typically 1.5 mm cracks) at start-of-life. The time for a crack to grow to failure must allow for multiple opportunities to discover it by inspection before structural failures occur. New technologies are treated conservatively.	ALARA
Nuclear power	Plant is designed to comply with established, conservative design codes that are enforced by national regulators. Plant is assumed to be 'defect-free' at start-of-life (or at least to contain small defects of size below the limits of detection techniques), with a 'safe-life' to be within the period of any crack initiation. Assessment of defects discovered during operation can require extensive calculations and assessment to justify continued use.	ALARA
Marine including offshore	Structures are designed for safe life, but the load cases are often not well-understood. Construction overseen by classification societies, but limited statutory regulation. Structures are inspected for damage, though with different approaches taken by offshore operators and ship owners.	ALARP Risk levels as high as 1 in 100,000 to 1 in 10,000 per year are routinely applied for certain systems, meaning that across the industry structural failure and even fatalities can be expected on a near-annual basis.

Industry	Approach to structural integrity	Level of acceptable risk
Road transport	The transportation sector has no explicit regulating authority. Designs must be fit for purpose. Damage-tolerant design is very rarely used: components are either designed for safe-life and/or eventual failure is accepted.	ALARP
Rail	Safe-life design for both vehicles and infrastructure. Inspection of rails increasingly replaced by preventive maintenance. No direct regulation of the system from a safety perspective.	ALARP
Utilities (gas, electricity and water)	Design is generally safe-life, but replacement often occurs when failures are detected: often no planned maintenance as design is effectively for infinite-life. No regulation of the system from a safety perspective, but codes of practice in place to ensure public safety.	ALARP
Renewables	Safe-life or infinite-life design. Inspection and repair often difficult, particularly for offshore installations, and can be hazardous. No formal regulation.	ALARP Failures very rarely physically impact either workforce or the public.

Sector perspectives: some examples

Nuclear power

In the UK nuclear industry, demonstration of structural integrity is overseen and enforced by the Office for Nuclear Regulation (ONR). Other countries have similar mechanisms in place to assure safety. The codes and standards used sometimes differ in terms of their basis and approach, but are designed to ensure the safety of the critical components of the reactor system.

> 'Structural integrity aspects of the safety case should be based on sound engineering practice and take account of the safety functions that need to be delivered. Taken together, the various elements of sound engineering practice provide defence in depth against a structural integrity failure occurring. Novel approaches and features may be acceptable provided they are supported by appropriate research and service to demonstrate the delivery of safety functions and are then monitored during service.'
>
> Source: ONR's 2014 Safety Assessment Principles for Nuclear Facilities Revision 0.

Codes and standards typically provide a set of procedures that distil a complex set of underlying physical phenomena into conservative engineering rules that can be applied quickly and efficiently by an analyst. It is important that the development of codes and standards keeps pace with ongoing developments in the understanding of structural failure modes to ensure that opportunities are taken to remove excessive conservatism while ensuring safety. To achieve this, industrial and academic engagement with codes and standards committees is vital.

Maritime and marine

A ship is a complex system comprised of nested sub-systems with a high degree of inter-dependency such that the ship can operate largely independently once it is at sea. Within the overall ship system, many disparate technologies interact, ranging from the ship's structure to the control systems responsible for propulsion, navigation and firefighting. Novel sub-system technologies offer opportunities for performance improvement, but this is not straightforward, as changing one system can have a knock-on effect to other system elements.

For example, conventional power generation systems in ships are based on diesel generators that supply the electrical power for the ship as well as its propulsion. Optimising the power systems for better efficiency, reliability and ease of maintenance are all challenges in their own right with existing technologies. When we then consider the opportunities presented by multi-fuel engines, storage and management of alternative fuels, emissions control, multiple and hybrid power sources, battery technology, automation and remote operation, autonomous systems, and more, it can easily be seen that there are enormous complexities facing the designers and operators of future ships.

Challenges exist in adoption of new materials of construction even though they offer improvements in properties and functionality. Examples include: the use of high-strength, corrosion-resistant and crack-resistant steels; increased use of composites; and the possibility of deploying novel additive manufacturing technologies (3D printing).

There is limited information and no formal database of structural, mechanical or electrical failures or near-miss events of ships in operation with sufficient and accurate background information. Because of the lack of a knowledge database, and uncertainties in design factors including seamanship (human factors), risk-based design has hardly been applied historically to ship structures.

Offshore

The offshore sector faces the challenge of operating complex bespoke systems such as rigs, production platforms, and pipelines, often in inaccessible locations where very limited external support is available. The financial impact of downtime is huge with oil production incomes often running into millions of dollars per day and rig hire costing hundreds of thousands of dollars per day.

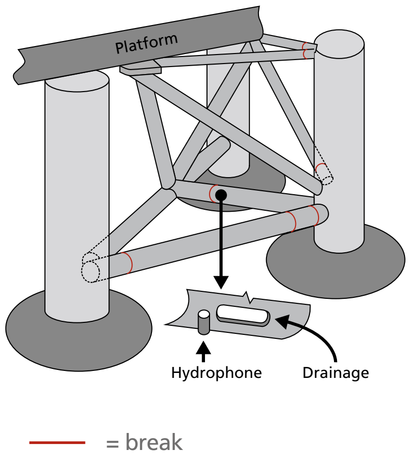
Given the remote location and high cost of downtime, offshore facilities have a need for high autonomy in addressing structural and equipment malfunctions and ensuring safety, which relates directly to the need for systems performance and structural integrity.

The Alexander Kielland was a Norwegian oil platform located 320 km east of Dundee, Scotland, owned by the US company Phillips Petroleum and built between 1973 and 1976 in France to an established design. The platform served as living quarters for the crew of the adjacent Edda platform. On 27 March 1980, while most of the crew were in the platform's cinema, a support bracing failed during bad weather. There was then a series of failures of other support braces, and one of the support columns which provide buoyancy to the platform, broke off. Twenty minutes later the platform capsized. Of the 212 people aboard, 123 were killed.

Alexander L Kielland and Edda by Norsk Oljemuseum - Norwegian Petroleum Museum

In the offshore sector current trends are towards operations in ever more challenging locations, deeper and farther away from shore support; and in harsher environments including Arctic and partly-ice-covered zones. Additional challenges come from a general trend toward longer service lives, both at design stage and in operation where service life extensions have been common practice.

Furthermore, new legislation and various other technology developments are driving the sector towards increasingly complex facilities. Both this increased complexity and the longer planned service life increase the maintenance needs, while at the same time the workforce age profile is such that large numbers of qualified workers are leaving the industry and are often replaced by a less qualified local workforce.



The investigation concluded that the platform collapsed owing to a fatigue crack in one of its six bracings. The fatigue crack had initiated from a weld which attached a hydrophone (an underwater microphone) to the structure. The weld was of poor quality and acted as an initiation site for the fatigue crack, that then grew around the wall of the bracing until final failure occurred by brittle fracture. The report also identified shortcomings in the overall design of the platform, with respect to its stability and buoyancy, and there was criticism of the emergency management procedures that were in place.

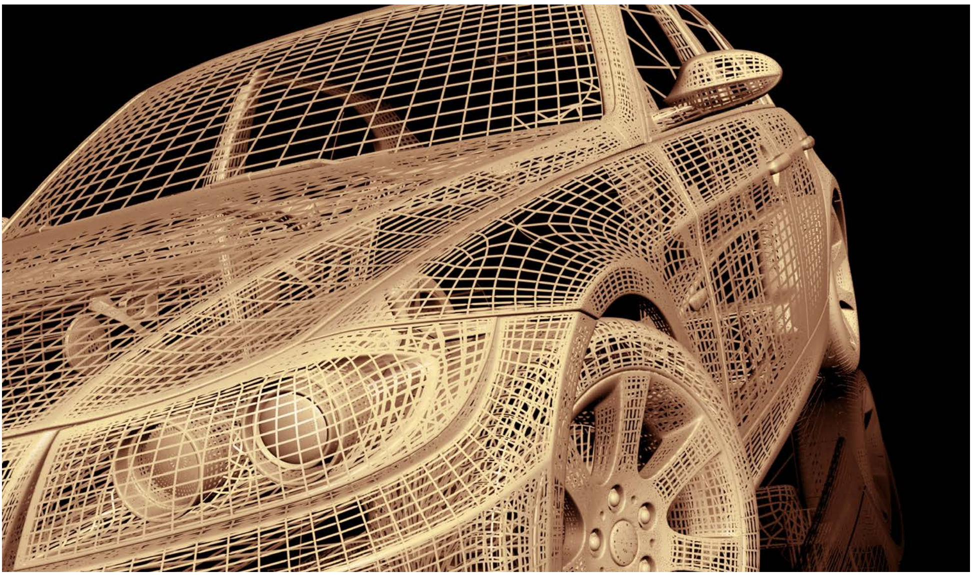
The causes of the disaster were therefore a combination of unknown sea loads, inadequate structural design to cope with those loads, poor manufacturing, lack of fail safety, and lack of consideration of crew protection in the event of a structural failure. This spans everything from poor weld integrity to the overall systems design.

Automotive

The current key drivers for the automotive sector are in light-weighting, fuel efficiency, and CO_2 emissions regulation. However, engine efficiency and electrification measures required to meet fleet emissions targets actually lead to increases in vehicle weight, so there are competing demands that designers must deal with. The automotive industry is of particular importance in the industrial context of light-weight materials usage: of the materials used by automotive, aviation, and wind energy combined, more than 90% is used by the automotive industry.

While designers are well-educated with respect to traditional materials such as sheet steel, and there are extensive design tools for these materials, this is not the case for many candidate advanced materials. For example, lightweight magnesium alloys could be used in vehicle structures to reduce weight but they require effective corrosion protection that does not currently exist.

Another example is the joining of materials that differ from the established techniques for joining sheet steels and aluminium components that are currently in use. There is a lack of



well-validated technologies for joining dissimilar materials, such as aluminium to advanced high strength steel, or combinations of more than two materials.

For composite materials there is a need to better understand how their properties are dependent on the early stages of the material production process, and also how damage develops in these materials during their life. Methods to predict composite performance need improvement in order to be used with confidence and to minimise the need for overdesign.

Additionally, composites are being used increasingly in the aerospace sector, replacing metallic materials which are better understood in terms of their failure mechanisms. Inspection of composites can be challenging, as can the interpretation of the impact of any damage detected on the future performance.

Infrastructure

Society depends on a critical infrastructure of water and energy supplies, communications and transport. All aspects of this infrastructure are continually increasing in scale, with ever more complex systems and systems-of-systems being developed and connected in large, increasingly globalised networks. In turn, these networks are also increasingly dependent on each other: consider, for example, the links between the rail, road, sea and air transportation networks; or the links between infrastructure, power, telecommunications and the internet.

Society depends on a critical infrastructure of water and energy supplies, communications and transport

This increasing complexity means that the failure of individual components, systems, assets and networks in today's critical infrastructure have the potential to cause major impact on society and life in general. Minor failures such as blackouts, road network delays, loss of water supply, and unavailability of computer networks are frequently encountered. Wider-reaching, more significant failures such as the loss of city underground rail services or widespread power failures are extremely rare, although they do occasionally occur, causing significant disruption (see overleaf).

North America, 14 Aug 2003. Ten million people in Ontario and 45 million people in eight US states were affected by a blackout lasting two days. A cascading sequence of events followed an overload in the electricity distribution grid that caused more than 508 generating units at 265 power plants to shut down and eventually led to a loss of pressure in water systems in several cities, overloading of mobile networks, interruption of most rail services with passengers needing to be evacuated from tunnels, disruption on the roads owing to problems with traffic light sequencing, and major disruptions at airports. The primary cause was a software bug in an alarm system that did not trigger effectively when power transmission lines came into contact with overgrown trees.

Italy and Switzerland, 28 Sept 2003. Fifty-six million people were affected by a 12-hour blackout caused by a power line damaged in a storm. Again, a cascading sequence of events quickly led to major transportation disruptions, with 30,000 people stranded on trains, 110 trains cancelled, all flights in Italy cancelled and several hundred people trapped in underground trains.

These are both significant failures in systems performance from relatively small initial causal events.

New developments, knowledge gaps and technical challenges

A core element of the workshops was to identify the current ‘hot topics’ that are challenging or will soon challenge the way that systems and integrity are understood and assessed.

The workshops identified challenges to the way that systems and integrity are understood and assessed

New materials, increasing complexity and a desire to reduce risk are leading to immediate gaps in knowledge. Systems need to perform efficiently and safely over longer periods in ever more harsh environments. Across the sectors that we have highlighted (see Table 1 on page 13) – which are a snapshot, and not intended to be comprehensive or limiting – technical challenges related to systems performance and integrity abound.

Design for maintenance and inspection

An offshore platform or floating facility, for example, has constraints associated with providing its function in the smallest possible footprint to reduce manufacturing and installation costs. Space-efficient solutions are ever more valuable but that often has a negative impact on ease of access for maintenance. The flaw in designing for low cost construction means that if a system is brought completely to a halt by routine maintenance, because of lack of thought or redundancy at the design stage, the whole-life cost can be significantly increased.

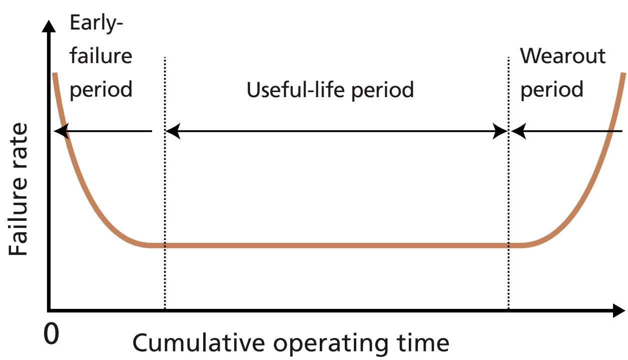
At the same time, operations during maintenance are one of the main causes of injury to the workforce, particularly in the oil and gas sector. Improving the design of installations for easier, safer inspection, and deploying new technologies to aid workers, will have a direct and positive benefit on the protection of life.

The development of more reliable and higher-resolution non-destructive examination techniques is making large advancements, particularly with sensors being integrated into structures at the start-of-life, and the use of drones for remote inspection. It is important to ensure that flaw detection and characterisation capability has a margin for error that is near-zero, taking full account of the human factors involved in interpreting and acting on the data obtained.

Increased lifetime

In all industrial sectors there is a very strong drive towards increased asset life in order to reduce whole-life costs. This applies to products as diverse as cars, computers, and oil and gas platforms, and leads to competition between technologies that can reduce weight and those that extend life. Being able to thoroughly and accurately assess an asset after decades of operation in order to determine its current health is of critical importance. Once again, there are sectorial differences that come into play: in aerospace, it is assumed that a structure will develop damage at an increasing number of locations as it ages; in automotive, structural parts are designed with an infinite-life assumption.

In some marine structures more intense inspection is often applied after commissioning to check for the consequences of construction flaws, if that stage is passed without issues then less intense inspection can be implemented. Then after perhaps 10 years of operation coating systems start to break down and from there on structural failure is heavily correlated with corrosion, so inspection and maintenance levels need to increase.



The bathtub curve showing failure rates over time

Life extension of nuclear power plant often is limited by time-dependent failure mechanisms, such stress-corrosion cracking or creep damage, which are neglected in the original design process.

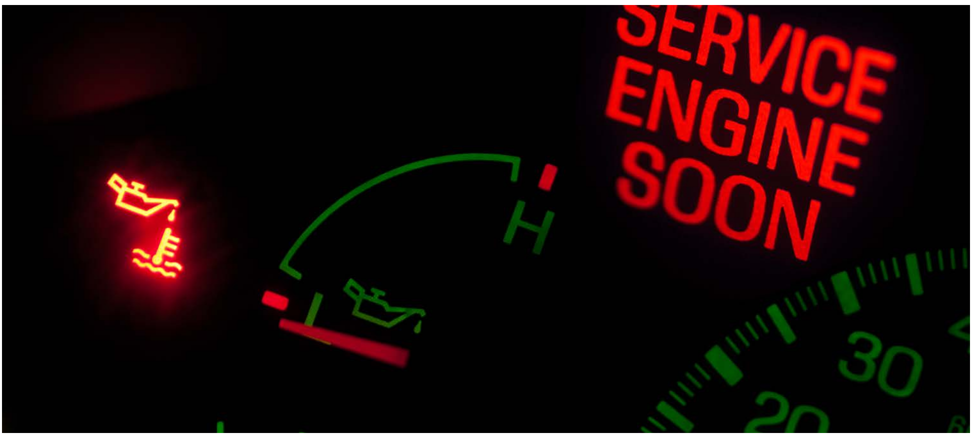
The need to ensure reclamation and recycling of materials at end-of-life is also a challenge.

Increasing complexity

More complex systems mean more individual points of failure. A faulty engine sensor in a car can immobilise the vehicle in the same way as an actual fault in the engine. That is an everyday example which causes inconvenience, however the equivalent event in a safety system on an offshore platform can lead to significant financial loss. Additionally, unreliable safety systems can lead to unnecessary or incorrect human interventions, or an assumption that a particular warning can always be ignored.

The complexity of structures and systems is increasing dramatically year-on-year. This applies to large-scale systems such as transport networks, but also to consumer products, which increasingly rely on both electronics and mechanical devices to deliver improved functionality and performance. Consumer electronics – such as cell phones, GPS trackers and game consoles – now integrate sensor technology, mechanical transducers and embedded software at low cost.

Highly complex problems are difficult to deal with in the framework of risk assessment and management because of the uncertainties involved. Integrated and multidisciplinary approaches need to be developed because more computation power itself is not enough to solve such problems. Testing with large- and full-scale test models is ideal but this is not always possible for bespoke, complex structures. Realistic simulations of structures and systems often lack accuracy because the real loading and environmental conditions are unknown or cannot be perfectly replicated by laboratory testing.



More extreme operating environments

In many applications, operating conditions are becoming increasingly aggressive as technology evolves. Turbine temperatures in jet engines are increasing; offshore platforms are operating in deeper waters and Arctic environments; oil and gas installations are handling hotter and more corrosive products.

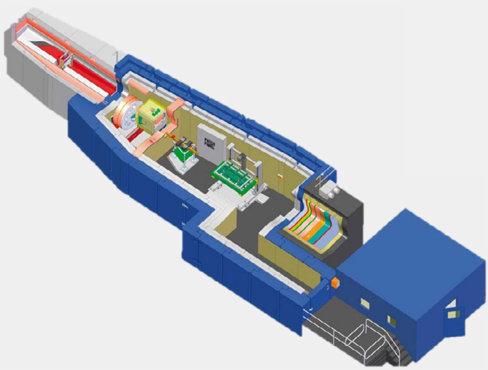
As electronics systems become increasingly miniaturised, and micro-chip technology moves to ever smaller length scales, issues arise with the potential effects of in-service failures, and how robust the individual components will be to factors such as elevated temperatures and electromagnetic interference.

Neutrons can cause 'single-bit' errors in memory or processor chips, or more catastrophic errors that can lead to failure of the hardware or the software system. For safety-critical systems in the air and on the ground, these effects must be understood so that mitigation and fail-safety can be put into place.

In harsh environments, there is the additional problem that sensing and measurement tends to be increasingly problematic, so that the baseline data required for design is often sketchy and unreliable.

High-energy cosmic rays can cause bursts of protons and neutrons at high altitudes that can disrupt electronic equipment. There have already been instances of temporary loss of control on modern airliners that have been attributed to these effects.

ChipIR is a new experimental facility being constructed at the UK's ISIS neutron and muon source. It will expose components to a high-energy, focused beam of neutrons, that will be able to simulate operating exposure of hundreds of years in just a few hours.



Understanding and quantifying risk and safety

Two competing approaches to design are to design against anticipated failures with the lowest practicable risk; and to take a risk-based approach which recognises that a failure may occur but at a defined low level of risk. In either case it is desirable that a defined level of safety is maintained.

The particular challenge in undertaking a risk-based assessment of a design or an overall system is that there may be insufficient understanding of the operating environment, failure mechanisms and their consequences to obtain a valid and useful answer. There has been much work in recent decades on probabilistic approaches to failure prediction, but such methods cannot predict the future, or deal with changes in the operating environment that change the 'input parameters' of the problem. It can be argued that risk-based approaches can never replace good understanding of the fundamental mechanics of a system, however, in some cases they are the only way of dealing with unknown factors.

As a consequence of the complexity of the marine environment, risk-based structural design has become one of the long-term strategic goals for the maritime sector. In that context, reliable cost-effective assessments are needed to control risks to be as low as reasonably practicable: though the question remains as to what is an acceptable level of risk.

The addition of new safety devices when they become available is not necessarily a panacea. Additional complexity in the system is a problem in itself. Any part of the system, even one which overall improves safety, is a potential source of failure in its own right and can therefore lead to downtime if it fails. The balance between over-measuring and ensuring the most simple and cost-effective solution can be difficult to achieve.

The balance between over-measuring and ensuring the most simple and cost-effective solution can be difficult to achieve

Gaps in knowledge and understanding

A large portion of the workshops was dedicated to scoping the question of what are the current gaps in knowledge and capability. By 'capability' we mean our current ability (or lack thereof) to model or measure the behaviour of a system or the elements within it. Two recurrent themes were measurement of the state of a material during its operating life, and modelling complex loading on engineering systems, particularly in the marine environment.

Many marine structural designs rely on prior experience and best practice to ensure strength and stiffness. The absolute failure loads for a structure are not known, and there is no whole-body testing to failure for validation and assurance.

There is a case where the uncertainties are from not completely understanding the structure, combined with a lack of complete understanding of the external environment – such as the combination of wave loadings – and how they interact with the structure. In a broader sense, this is indicative of a lack of understanding of the overall systems performance: where we have multiple areas of ignorance in a design there is then a requirement to take a different, risk-based approach.

In some cases, in-service monitoring of critical information is not possible with existing methods: an example being that the integrity of mooring cables for floating platforms is generally unknown until a failure occurs.

Novel materials pose problems for designers. While static properties such as strength are easily determined, how that strength degrades over decades of in-service exposure is effectively unknown. An excellent example is given below for materials in nuclear power applications. Another current example is the increasing use of composite materials in aerospace: including the use of carbon fibre composites as structural members but also the use of metal/composite laminates and assemblies. The mechanisms of fatigue degradation are entirely different from conventional metallic systems, which pose challenges for lifing techniques, and also inspection and maintenance.

In service, nuclear reactor components are subject to high pressure and high temperature environments and severe thermo-mechanical cyclic loading. The operating environment itself typically acts to enhance material degradation mechanisms, for example:

- hardening and embrittlement of pressure vessel steels resulting from irradiation damage
- oxidation of steels in the carbon dioxide environment of advanced gas-cooled reactors
- corrosion fatigue and the degradation of fatigue performance of stainless steels in pressurised water reactors (PWRs)

- corrosion of the zirconium alloys (used to clad the nuclear fuel) in water
- stress corrosion cracking and irradiation-assisted stress corrosion cracking in boiling water reactors and also PWRs.

These material ageing and degradation modes have the potential to erode start-of-life safety margins and as such the development of a fundamental understanding of the underpinning mechanisms is key. The ability to understand and predict material degradation in response to loading and environment is important in demonstrating that potential failure modes are gradual and predictable. With the current efforts in new build for nuclear power worldwide, these are immediate and important challenges to address.

The Boeing 787 airframe uses carbon-fibre-reinforced plastic and other composites to provide weight savings compared to conventional metal-based designs

Research gaps

The end-point of the workshops was the identification of the high-level research themes that will deliver significant impact in the domain of structural integrity and systems performance. The four themes that were identified can be summarised and grouped as:

- materials and degradation
- measurement and sensing
- simulation and modelling
- systems, complexity and risk.

In addition, a strong theme of knowledge transfer was identified that, although not a research theme *per se*, was found to be an area of potentially very high impact for structural integrity and systems performance. We have therefore highlighted this as a theme in its own right.

The workshops identified five themes that will deliver significant impact in the domain of structural integrity and systems performance

Materials and degradation

The performance of materials is one of the most critical factors in the integrity of a manufactured component or structure. Research into materials failure has been at the forefront of technological efforts for decades, and is likely to remain so as the portfolio of materials available to designers continues to evolve and increase, and the requirements for materials to withstand more complex, more challenging, and more aggressive environments become ever more demanding. An example is the use of materials for bio-prostheses, where the effects of exposure to bodily chemicals for decades is simply unknown at the point where they are first used. At present there are advances in the field of additive manufacturing (so-called 3D printing) where the novel structures produced are yet to be fully characterised for their lifing and damage tolerance.

There were numerous areas that were identified that constitute research gaps not currently being addressed. While it is accepted that much funding is directed to developments in novel materials – with graphene being perhaps the prime example – 'conventional' materials are often overlooked, particularly in terms of asset management for ageing systems, which is seen as being an ‘operational’ problem rather than a valid engineering research theme.

Areas of research need can be summarised as:

- **Materials degradation and failure.** Measurement and prediction of damage development during life and methods of accelerated testing to be able to predict performance and remnant strength after perhaps several decades of operation. Prediction of life needs to be able to account for the influence of accidental loads, for example, on overall performance. The effect of repair strategies must be thoroughly understood. Whether or not accidental damage or manufacturing flaws will lead to failure is a current unknown that has only empirical solutions.

- **Multi-scale characterisation and modelling of materials** from atomic level to a full component level. There is a gap in modelling capability between the atomic scale, where there is excellent understanding of the physics, and the macroscopic scale, where the mechanics can be accurately reproduced. At the ‘mesoscale’ the situation is much more difficult to model reproducibly and in a way that is transferable between material systems.

- **Inspection and characterisation tools.** Tools for assessment of the damage state of a material, non-destructively and during operation, would be a significant advance. Proxy measures for determining damage, such as geometric changes of the overall structure, or acoustic emissions from cracking, can be of value but require new knowledge of how such events occur and can be characterised.

- **Understanding residual stress.** The evolution of residual stress from in-service loading can drive failure mechanisms. Off-line monitoring and characterisation can also provide useful data for life prediction.

These latter two link to the next theme of measurement and sensing.

Measurement and sensing

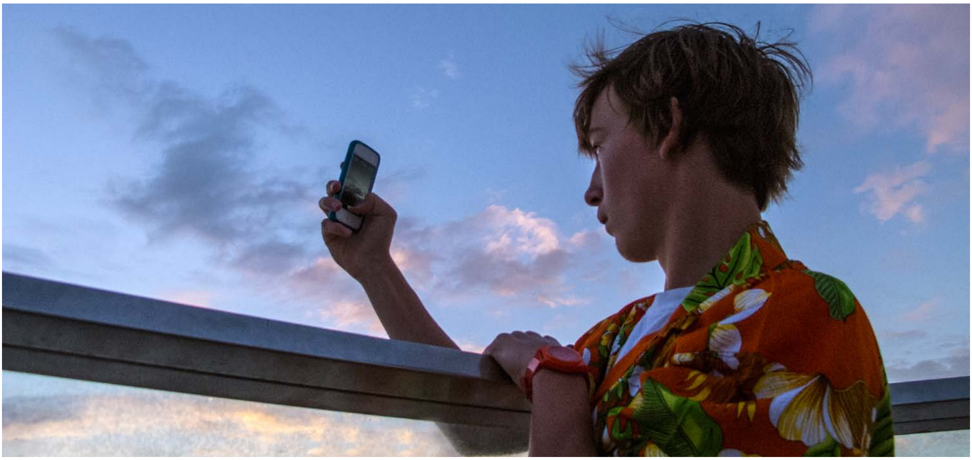
Following on from the materials theme, some of which reflects the need for measurement of properties and damage, there is a broader need for advances in measurement and sensing to fully characterise the performance of a system and the elements within it. Some of these requirements are for the characterisation of the environment within which assets are operating; others are to do with health monitoring of the structure or system itself.

The increasing complexity of critical infrastructure means that systematic methods must be identified to determine what data to measure, and when, where and how this can then be used to inform critical decision making. A prime question at the design stage is: what data are needed and how will they be handled? The concept of 'design-for-data' needs to be developed for safety-critical industries. Collecting data from a structure and not using it can lead to claims of negligence if it is subsequently shown that evidence of an imminent failure was present if only the data had been analysed.

Research challenges here include:

- **Sensor development.** An interesting development is whether existing parts of a system, such as fibre optic cables, can also provide information on, for example, local strains, alongside their communication function.

- **'Crowdsourcing' and communication protocols between sensors.** For a large vehicle such as a cruise ship, could the accelerometers present in all the smartphones carried by the passengers be used as a health monitoring tool?



Could the accelerometers present in all the smartphones carried by the passengers on a cruise ship be used as a health monitoring tool?

- **Data filtering.** With distributed sensor networks comes the possibility of distributed processing power that can mitigate the problem of enormous volumes of data being generated. Part of the design-for-data concept is having the data in a valuable and usable format. Using local processing in a sensor network to filter data in a way that adds value can provide immense benefit so that only the 'valuable' information is finally transmitted to a central monitoring point.

- **Database curation.** There is considerable value in the development of a database of operating environment and structural response where there are current knowledge gaps and uncertainties. An example is the forces generated on floating platforms in ice fields. If agreement could be reached on data sharing through a trusted, neutral broker, valuable information could be gathered to inform future research and designs. An interesting concept for marine structures would be the development of a 'marine observatory' to collect long-term data on sea conditions, and the corresponding response of a structure.

Simulation and modelling

Advances in computing power and developments in numerical analysis techniques mean that more complex analyses can now be undertaken on a routine basis, encompassing more complex materials and structural responses. Engineering assessment procedures typically employ a hierarchical approach by which a simple analysis is undertaken in the first instance and more complex analysis is undertaken only if insufficient margin can be demonstrated by the simplified approach.

Such approaches are intended to provide a conservative assessment and work well in isolation. They can be inefficient when conservative assessments are passed from one stage of the design and manufacturing process to the next, leading to an overall design that is sub-optimal and overly conservative.

Novel modelling frameworks must be developed to allow the integrity and resilience of complex systems, assets and networks to be predicted, to allow vulnerabilities to be identified, and design improvements and upgrades to be targeted for maximum positive impact. A key factor in modelling is whether or not the 'right' answer can be obtained. The development of evidence-based criteria for model acceptance and testing would be a useful step forward. An important area where increased modelling fidelity is expected to become more critical is in the simulation of difficult and costly tests to replace physical testing.

A valuable advance would be the ability to inform structural design with the processes by which materials and components are combined to form the whole structural artefact, accounting for strains and stresses induced by the cutting, forming and joining processes in metals, for example, or flow and curing processes in polymeric materials.

The modelling of complex structures remains challenging and the results unreliable. The fundamental physics of load transfer in structures merits additional study, and in the short term novel experimental procedures to provide the input data to both numerical and theoretical modelling are of high value.

Systems, complexity and risk

This theme goes to the core of systems performance. While it is tempting to focus on a particular material or failure mechanism, a specific structure, or the advantages of a new type of sensor, assuring the safety and integrity of the overall system is the end goal. Because many systems are indeed complex, making them difficult to analyse and making it difficult to reliably assess the risk of failure and associated consequences, the temptation is to focus on sub-elements of the system for simplicity, leading to an overall solution that is not optimised. Furthermore, adding complexity and even new safety systems can reduce reliability - and even safety, because there are more potential points that can fail.

In mature industries, developments are generally incremental: to the layperson unaware of the immense developments in engine and materials technology, a Boeing 707 looks essentially the same as a Boeing 787 despite being separated in design and manufacture by half a century. Aerospace industry targets for emissions, fuel-burn and noise reduction are challenging and will be difficult and expensive to achieve via incremental developments. Moving towards next-generation turbo-electric propulsion systems will require a radical redesign of the entire airframe concept, and a fundamental change in the industry business model – which is currently based on engine suppliers bolting engines onto an airframe – towards an integrated design involving engine suppliers and airframe manufacturers implementing novel electrical distribution systems. Of course, in addition, there are a whole set of materials, reliability, power storage, and condition monitoring challenges associated with this.

Taking a whole-systems approach requires analysis of the business models that underpin the development of safe systems, so that risk, integrity and safety are part of the value and decision chain. This then needs methods for application of risk-based analysis techniques to allow targeted design improvements that will bring the maximum possible benefit to system performance and resilience.

Assuring the safety and integrity of the overall system is the end goal

Knowledge transfer

As already observed, this is not necessarily a field where there are definable research challenges to address: but there are actions that the Foundation can take that will make a difference.

Industry-to-industry
Table 1, on page 13, indicates clearly that different industrial sectors take different approaches to structural integrity. The way that they take a systems-wide approach to performance at the design stage also varies markedly.

Many of the tools and techniques required to measure and evaluate system performance and establish performance criteria already exist, for example, risk profiling, ALARP, human-systems interaction; and are applied effectively within individual sectors. However, the ability to consistently and cost-effectively apply a common and appropriate set of tools and techniques across all sectors does not exist in any usable guise and would be a major step forward could it be realised in practice.

There is, of course, the fact that within a particular sector the approach taken to structural integrity and systems performance 'works', and has been refined over many decades. There are very different cost drivers in marine construction compared to nuclear power; and different levels of risk acceptance in the offshore oil and gas industry (where the risks are primarily to the workforce) compared to the aerospace industry (where the risks are primarily to the public).

We concluded that a scheme of knowledge exchange between industries would be of benefit in sharing best practice and challenging embedded customs. This could be reinforced by an initiative to emphasise different approaches to safety and risk in discipline-specific engineering degrees, so ensuring that marine architects appreciate damage-tolerant design and ALARA approaches, for example. The intent would be to promulgate those design philosophies and engineering principles that lead to the safest possible outcomes.

Generation-to-generation

There are various sectors of the global engineering industry that are facing problems because of changing demographics. The most obvious example is perhaps that of the nuclear power industry, where there was an intensive programme of construction from the 1950s to the 1980s which then tailed off as the technology fell out of favour. There is now a resurgence of activity, particularly in China, but also in Europe with many new plant commissioned or planned. However, the gap in construction has led to a shortfall in knowledge and skills across the sector to underpin the new-build process. and some of the current build projects have faced problems as a result of issues within the supply chain that would have been unlikely if construction had been ongoing as in the oil and gas sector, for example. There are also issues in introducing newer materials and manufacturing techniques into a system based on historical codes.

A programme of work into knowledge capture methods for experienced engineers would be of immediate and future value in ensuring that expertise and know-how can be accessed by future generations. Not everything finds its way into textbooks, and much that was written in the form of technical reports in the 20th century has now been lost. An open, validated and informed 'engineering Wikipedia' built on practical experience in conjunction with basic principles would be of immense advantage to practising engineers as well as students and their teachers.

Finally, another generational issue for engineering knowledge transfer is the skills gap that is developing as a result of the ageing workforce in engineering, with a dip in numbers in the profession as a result of weak recruitment and headcount reductions over the last 20 years. While recent recruitment into engineering courses at university level has improved significantly, partly driven by good starting salaries for graduates, there will still be a shortfall that needs to be addressed. This need links to the Foundation's strategic theme of advancement of skills and education. There are opportunities for reskilling of workers from other industries, up-skilling of workers from technician to engineer level, and to continue work on attracting talented young people into engineering careers.

The area of knowledge transfer is seen as linking to the Foundation's other theme of resilience engineering, as the provision of a suitably qualified and experienced workforce is critical to the continued safe operation of any technically-complex industry.

Recommendations

The Lloyd's Register Foundation has finite limits on what it can support. For this reason it is necessary for the Foundation to select challenges where it can make a distinguishable difference. Taking the outputs from the workshops and the consultation process, and aligning them with the charitable aims of the Foundation, the following challenges have been identified as recommended priorities for future development:

- the safety of systems containing 3D and 4D additive manufactured parts
- engineering science challenges: advancing the state-of-the-art to maximise safety
- development of an economic whole-system approach to demonstrate safety and integrity
- data-centric engineering
- minimising the risks associated with maintenance and inspection.

The safety of systems containing 3D and 4D additive manufactured parts

The potential to create a component from raw materials by additive manufacturing (sometimes called AM or 3D printing), anywhere in the world, at low cost and with high speed and quality, has the potential to revolutionise manufacturing industry. Shipping costs and lead times will be vastly reduced, with some analysts predicting a reduction of up to 40% in shipping freight once the technology becomes established. While applications of AM in safety-critical structural components are currently rare, this will change rapidly as the technology advances.

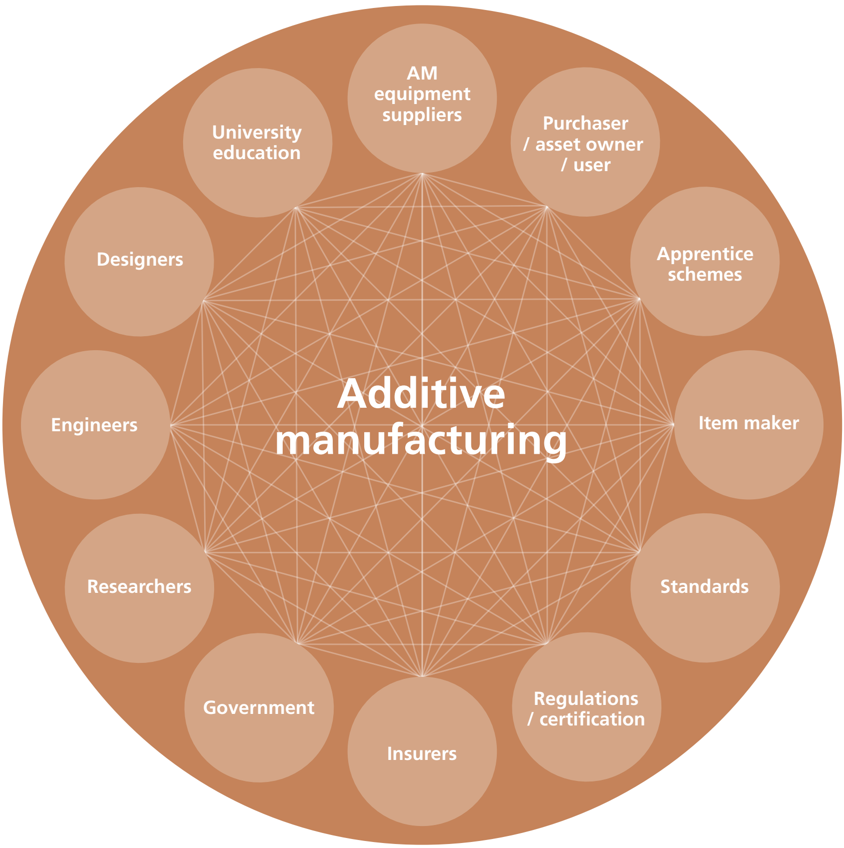
Globally there is a diverse and intensive research effort into AM design and manufacturing techniques. Significant effort is being deployed to solve the barriers to its implementation and as such it is difficult to have or maintain a clear overview of the current state of development.

The opportunity exists for the Foundation to act as a catalyst to bring together all stakeholders, from researchers through to users and regulators, with the aim of identifying the key issues that need to be addressed to ensure the safe application of parts made using this developing technology. This is anticipated to include development of manufacturing skills, standards, certification, legal responsibility, and underpinning research. The findings of this and any subsequent forums will be openly published.

Until such a time as the research gaps are identified, the Foundation should consider investigating the following:

- the new field of 4D printing, where the shape of a 3D printed item can change by a self-activated process triggered by the operating environment

- research into the mechanisms of in-service degradation to ensure long-term integrity of additive manufactured parts; and
- that appropriate recognised training exists for those that will operate and create parts by additive manufacturing; this links to the Foundation's strategic theme of skills and education.



Stakeholders in safe application of additive manufacturing

Engineering science challenges: advancing the state-of-the-art to maximise safety

The advancement of engineering science has the potential to provide the community with knowledge, know-how, and products to demonstrably support and enhance safety and reliability.

The recommendation to the Foundation is to select and support topics that become enablers for new ways of predicting or mitigating engineering risks.

Below are three exemplars identified during the review that have potential to have far-reaching impact.

Complex loading
Marine and offshore structures are complex in nature and operate in an environment that is difficult to characterise fully. Surprisingly, we lack a detailed understanding of how the environment (for example, waves and ice) interact with structures and generate stresses at the local level, and how these build up over the total structure and effect long term performance of the system. Research is required to develop the fundamental knowledge of how force is transmitted between the environment and structures, and how resulting stresses in a complex structure affect the assumptions currently made on integrity and reliability.

Residual stress engineering
While it is now possible to model how residual stresses develop in a simple coupon during welding, for example, modelling of the stresses in an entire structure after fabrication, and how they alter during service is important but not well understood.

A relatively new concept is that of residual stress engineering, which extends existing knowledge to deliberately applying residual stresses to a structure to increase fatigue life. The aerospace industry has had some preliminary success with residual stress engineering using laser shock peening (LSP) to reduce the initiation of fatigue cracks in titanium alloys.

The applicability of introducing intentional residual stresses into other materials and structures during design, fabrication or service to slow down, stop or divert a crack could result in safer methods of maintaining integrity without reducing reliability but requires significantly improved knowledge around residual stress engineering.

Assurance of coatings

It is essential to have confidence in the long term performance of a coating, particularly when it is applied in an environment that is corrosive to the material being protected and when the coating is difficult to inspect or repair.

Coating technology is constantly improving. With the use of appropriate coatings it is possible to make simpler systems that require less maintenance and repair, can operate in more aggressive environments, and allow the use of standard materials and fabrication technologies which are well-understood.

A barrier to application is an understanding of how new coatings perform over long durations of time in their operating environment through short term testing.

The ability to assure long-term performance of coatings from a short-term testing and/or modelling programme would have significant impact.

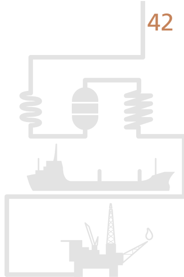
Whole-system approaches to demonstrate safety and integrity

The review has identified that different industries take different approaches to assure assets and systems are safe and dependable.

For example the aviation industry takes a low risk approach. It has methods to simulate the performance of all components in an entire aircraft to ensure that all the systems work together and maintain safe operation once planes are constructed and in operation. Once in operation, if design flaws are discovered, strict systems are in place to ensure modifications are made across fleets. In addition the aviation industry operate these aircraft within a wider aviation system which is well controlled and understood. This wider system includes for example, air traffic control, ground handling, maintenance, passenger security, and accident investigation etc. Such an approach has led to standardisation of systems and controls across not only individual aircraft, and aircraft fleets, but also across the aviation system as a whole.

In contrast in some industries the level of integration at the design stage is often limited. In commercial shipping components of a system are purchased from multiple sources and connected together in the shipyard without simulating how the finished system will perform. Any weaknesses of such systems are then uncovered during sea trials or more significantly during operation. There is potential to transfer and adapt systems integration approaches from the aviation industry at the design stage of a ship to assure safety and reliability.

The Foundation should support the development of innovative new approaches to whole systems safety in critical infrastructure sectors. In addition to developing new approaches, the Foundation should promote sharing and translation of best practice across industries and academic disciplines with the aim of improving the safety and dependability of whole systems.



Data-centric engineering

As we move into a data-rich technological framework, gathering and exploiting the 'right' data in a way that enhances safety will provide benefit beyond historical trial-and-error approaches. The Foundation's Foresight review on big data has already highlighted the potential enhancements to safety and reliability that the data revolution can provide via data-centric engineering. The recommendations made below focus on three aspects of data relevant to the scope of this review.

Design for data
This challenge aims to set data at the core of design. Methodologies will be created to identify which data are required in order to provide confidence in real-time feedback and predictions of individual components, systems and assets.

Data availability
To maximise the potential of big data there is a need to bring together as much relevant data as possible. Current obstacles to this range from data being maintained behind firewalls, owing to commercial sensitivity, to owners not understanding the potential value of the data they possess for themselves or the wider community.

This challenge will work to identify ways of increasing data availability that will most likely include data anonymisation, the hosting of data that is of an acceptable quality, and appropriate standards. It can be argued that when a license is granted by society for the operation of an asset or system then society should have a right to the data related to safety being made available for public use including academic research and system improvements. The Foundation is well placed to work towards increasing data availability.

Analytics
The power of big data rests on the ability to analyse the data quickly and infer what actions are needed. The development of analytics, and the individuals that are trained to develop them, are key to maximising the potential of data.

The Foundation's Foresight review on big data has resulted in a grant to the Alan Turing Institute to develop data-centric engineering and the resources essential for its success. The work of the Alan Turing Institute should be co-ordinated with activities recommended in this review for maximised impact.

Minimising the risks associated with maintenance and inspection

In heavy industry, casualties occur most frequently during maintenance and inspection operations. Human intervention for inspection and maintenance creates hazards for both the individuals concerned and the item being maintained. In 2013/14, maintenance and construction tasks in the offshore industry accounted for just under half of all injuries, with 70% of those classified as major injuries. This challenge focuses on reducing the frequency at which people and in-service assets are placed at risk.

There are three ways in which inspection and maintenance risks could be reduced or eliminated:

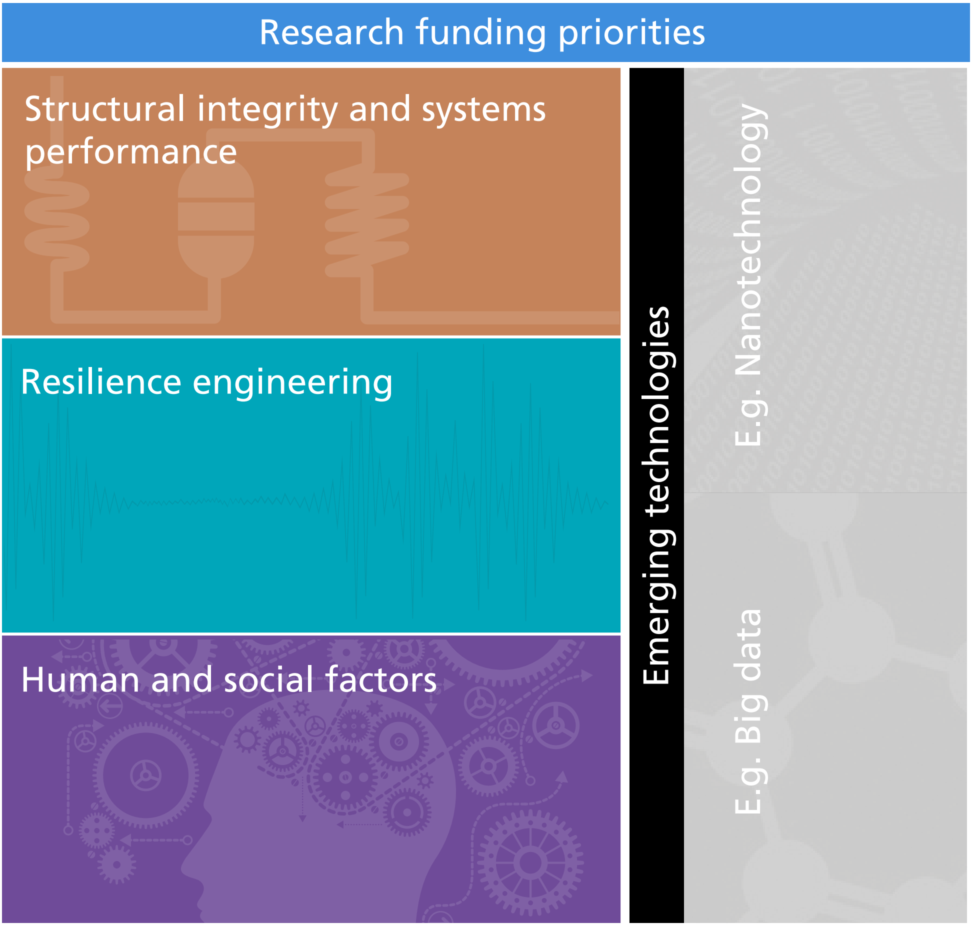
Use drones and robots to conduct inspection and/or maintenance
The subject of robots, drones and autonomous systems is already a large area of research and was beyond the expertise of the review panel. It is recommended that the Foundation conduct a separate review in this area.

Develop assets and systems that are able to monitor their own condition
Maintenance-on-demand requires the development of active or passive sensor technology that is able to provide a warning, through an intelligent system, when inspection or maintenance is required. Some such systems are already under development for specific applications. Although many sensing technologies already exist, they can have limitations based upon power requirements, communications, explosion risk, reliability, lifetime, and other factors.

There is scope to develop improved sensing technologies that, both passively and actively, can permit the development of systems that can monitor the asset. These could include, but are not limited to, ubiquitous sensing via nanotechnology (where there is potential overlap with the Foundation’s Foresight review on nanotechnology), proxy measures such as paint that ‘bruises’ to show areas of structural overload, or passive sensors activated by a defined action, such a piezoelectric-based sensor that delivers a radio pulse when loaded above a certain strain.

Design and build structures and equipment that require no maintenance or inspection
This solution is often considered to be impractical owing to expense, lack of technology, or uncertainties. The Foundation could consider two aspects: reducing uncertainties related to operating conditions through the construction of ‘data observatories’; and studies on simplification of complex designs to determine if it is possible to engineer out the need for inspection and maintenance.

Research funding priorities



The Foundation's research priorities should not be viewed in isolation; they are interlinked and can be understood at different scales. These range from nanoscale materials to individual components within complex systems to the interconnected networks of infrastructure on which society depends, and from the actions and behaviours of individuals of organisations and wider society.

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