DESIGN LIFE OR SERVICE LIFE: WHAT IS THE DIFFERENCE?

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INTRODUCTION

Many construction law cases involve an intersection of legal and technical issues related to a constructed facility, such as defects, fitness for purpose, durability, strength, serviceability, maintainability or operability. The common denominator of these issues is the design of the facility.

The design of a constructed facility involves all the large and small decisions required to determine its form, how its elements work individually and in combination to fulfil their functional requirements, what materials will be used in construction, how these are connected together, how the facility is to be constructed, and how it should be maintained and operated. It is the design that determines not only the form and nature of the construction, but also the economic characteristics of the constructed facility such as its durability, the ongoing operating and maintenance costs and ultimately its commercial life.

This paper discusses a number of aspects of structural design to explain the difference between design life and service life, an issue that may be important in the context of design and construct contracts. The "default" legal obligation to prepare a design with due skill and care is contrasted with the common contractual obligation for a constructed facility to be fit for purpose. These issues are illustrated by reference to recent case law.

DESIGN OF CONSTRUCTED FACILITIES

Those responsible for the design of constructed facilities are constrained by, inter alia, the laws of physics, the known, available and usable mathematics, and the known "state of the art" of the relevant technology. Notwithstanding the continual advances in technology and the "state of the art", the design and engineering of facilities "for the use and convenience of man"[1] will continue to create new frontiers, and reveal hitherto unknown gaps in our knowledge. In this paper "**state of the art**" refers to the art and science that would be applied by competent and experienced practitioners involved

[1] The 1828 Royal Charter Institution of Civil Engineers defined civil engineering as the "art of directing the great sources of power in nature for the use and convenience of man".

in the relevant practice of civil engineering, not necessarily the science of engineering as known to academics researching at the cutting edge of known technology.

Notwithstanding the availability of cheap and extremely powerful computing facilities, and the evolution of new technologies such as artificial intelligence, in this writer's view the design of facilities will (at least for the foreseeable future), rely on the skill and professionalism (including both art and science) of engineers and other professional practitioners. We can reasonably expect and require that those professionals be trained, skilled, experienced and up to date with "the state of the art" as defined above. Does that mean that they can "guarantee" a specific outcome in respect of the facilities they design? Specifically, can a designer, using up to date and "state of the art" knowledge, guarantee that a facility will have a specific service life in every situation?

All **facilities** in the subject of construction law (buildings, infrastructure, facilities for the extraction of natural resources, facilities for the processing of natural resources into manufactured products etc) are designed on the basis of certain assumptions, to perform specific functions over a service life (which may be implicit). The functions, assumptions and service life will be referred to as the **design parameters**, as these are the parameters that the designer must take into account in designing the facility.

A facility as a whole, and its individual components must be designed individually and collectively so as to comply with the design parameters.

Whilst certain parameters may be precisely known or are able to be calculated, many parameters can only be estimated on the basis of mathematical calculations, statistical measurement, experiment or engineering experience. For example, the required functionality may be capable of precise definition (e.g. a power station required to generate 500MW of power at a 90% availability for a service life of 30 years), whereas other parameters fundamental to the design may have to be determined by experiment, e.g. the practically achievable thermal efficiency of the coal fuelling the power station. Important design parameters arising from the forces of nature, such as wind loading, earthquake loading or the maximum anticipated flood level, are generally determined on the basis of professional consensus based on experience at the relevant location and statistical analysis of the available records.

The Institution of Structural Engineers UK defines structural engineering as "*The science and art of designing and making, with economy and elegance, buildings, bridges, frameworks and other similar structures so that they can safely resist the forces to which they may be subjected.*"[2]

[2] Campbell, Peter (ed) 2001, *Learning from Construction Failures: Applied Forensic Engineering.*

THE ART AND SCIENCE OF ENGINEERING

All branches of engineering involve both "art" and "science". Our understanding of physics and chemistry, and our ability to apply mathematics to their application in practical situations is the "science" of engineering. That science, aided by the enormous computational power of computers, is always evolving and developing to open up new frontiers in engineering. However, the "art" of engineering remains – the ability to know what and how much science to apply to a given engineering problem, in the face of an ever expanding knowledge base. An important parameter in that decision is (usually) the requirement to prepare, at a reasonable cost, a design that represents value for money. This may implicitly limit the extent to which sophisticated and expensive computer analyses are warranted.

Some areas of engineering are more amenable than others to the rigorous application of physics, chemistry and mathematics. For example, the design of a jet engine to operate flawlessly over a required number of hours before maintenance, has a much higher confidence level than determining the actual loads a bridge may be subjected to during its intended service life.

The focus in this paper is on what may be termed civil engineering facilities (roads, bridges, building structures, wharfs, tunnels etc), rather than mechanical, electrical or electronic components. Each civil engineering facility is unique – at least to the extent that every structure is attached to a different part of the earth's surface, and subject to environmental conditions unique to that location. Different functional requirements are also common, even between apparently similar facilities. In addition, major elements of a civil engineering structure must be built on site. On the other hand, mechanical, electrical and electronic components are generally produced to comply with well-defined input and output parameters, in quantity and in factory controlled conditions. The production in quantity enables incremental refinement and evolution over a long period of time. For example, modern day turbines have a higher efficiency and reliability than those designed 20 years ago.

The design of civil engineering structures involves a number of design parameters that are typically not known with precision. Some of the most important of these parameters are the properties of naturally occurring materials, the environmental conditions that a structure may be subjected to during its life, and the loads it must withstand in service or under extreme events.

In a case involving the failure of an offshore structure, Lord Justice Jackson made the following pertinent comments about the random nature of environmental loads:

> "J101 *[DNV international standard for the design of offshore wind turbines]* is, as Mr Streatfeild-James submits, stochastic. Weather conditions at sea and the forces which will be imposed upon offshore structures cannot be predicted with certainty. The authors of J101 prescribed what needed to be done in order to create a structure which has a

sufficiently high probability of functioning for 20 years. Paragraph F301 in section 2 provides a good illustration. In ULS *[ultimate limit state]* design the designer is required to assume a characteristic combined load which is likely to occur once in 50 years. In any given year the chance of that load being imposed upon the structure is only 2%. Nevertheless, this is not a matter about which there can be certainty. It is possible, although unlikely, that that combined load effect will be exceeded in year 1, again in year 2 and so forth. The authors of J101 regarded paragraph F301 as appropriate for a structure with design life of 20 years. No-one suggests that that provision would achieve a structure with a guaranteed life of 20 years."[3]

STANDARDS

Civil engineers use a variety of tools to cope with these ill-defined parameters, to design structures that, in the main, safely and satisfactorily perform their required function over their service life. Codes of Practice, or Standards, are an important part of the civil engineer's armoury. A Standard is generally the consensus view of skilled practitioners working in the specific field of the Standard, as to what constitutes current good practice, i.e. the "state of the art" of the competent practitioner. The detailed and formal processes involved in writing or amending Standards means that they do not represent the state of the science or technology the most knowledgeable academics or practitioners might employ. However, Standards are of great assistance to the ordinary practitioner in defining what standard the ordinarily diligent and competent practitioner should achieve, or what parameters should be used in design. They are not meant to be a straightjacket, and diligent and competent engineers may choose not to follow all the requirements of a Standard if they have a sound, rational engineering alternative. However, an engineer's use of an alternative approach that resulted in a lesser strength than that defined in the relevant applicable Standard could be very difficult to justify legally in a failure situation, on the basis that the Standard represents a widely accepted consensus view within the profession of the "state of the art" that an ordinarily diligent and competent practitioner should apply.

Standards are frequently cited in construction contracts, both in general terms, and specifically in a detailed list of Standards to be followed. For example, the FIDIC Yellow Book requires that: "*The design, the Contractor's Documents, the execution and the completed Works shall comply with the Country's technical standards, building, construction and environmental Laws, Laws applicable to the product being produced from the Works and other standards specified in the Employer's Requirements, applicable to the Works, or defined by the applicable Laws.*"[4]

[3] *Mt Højgaard A/S v E.ON Climate and Renewables UK Robin Rigg East Ltd* (CA) [2015] EWCA Civ 407; [2015] BLR 431, paragraph 93.

[4] FIDIC, *Conditions of Contract for Plant and Design Build for Electrical and Mechanical Plant and for Building and Engineering Works, designed by the Contractor* (1st Edition, 1999) (The Yellow Book), sub-clause 5.4.

The Technical Requirements that typically comprise one of the contract documents in a design and construct contract usually specifically define the Standards that must be complied with. Such Technical Requirements are normally prepared by engineers who are skilled and experienced in the particular type of facility. In this writer's view, such engineers should be selective and focussed in the Standards that they list. It is less than helpful to have Standards from different jurisdictions listed if the specified requirement is to satisfy the highest standard from those different Standards. Such an approach does not take due account of the different basis on which the Standards were prepared, nor of the possible jurisdictional differences. It is an unnecessary fetter on the designer, and may lead to confusion and unnecessary extra cost in design and checking, without necessarily resulting in a superior product.

It is significant that modern standards are based on a recognition that design parameters are inherently variable, and cannot be predicted with certainty:

> "Recently revised national and international standards for structural design are systematically based on probabilistic concepts, mathematical statistics and on the theory of structural reliability. The International Standard ISO 2394:1998 and EN 1990:2002, based on materials of JCSS [Joint Committee on Structural Safety], play a key role to constitute a common basis for defining design rules relevant to the construction and use of the wide majority of buildings in civil engineering works (ISO 13822:2001, ISO 22111:2007)."[5]

RELIABILITY

Reliability is the probability that a system will perform its intended function for a specific period of time under a given set of conditions. Reliability is also the probability that unsatisfactory performance or failure will not occur.

Structural reliability is an overall concept covering structural actions, response and resistance, workmanship and quality control, all of which are mutually dependent. Structural reliability is quantified in a **structural reliability index**. The calculation of this index depends upon the mean values and coefficients of variation of actions and resistance. The calculations also assume that the levels of workmanship and quality control are maintained in accordance with current standards, and are appropriately accounted for in the resistance model. It is applicable to the design of structural elements. "*The reliability index could be thought of as a form of safety factor that includes the uncertainties in the determination of the actions and resistances.*"[6]

The Australian National Construction Code states that the structural performance requirements are verified for the design of structural

[5] M Holicky & JV Reteif, "Probabilistic basis of present codes of practice" in Zingoni (ed), *Advances and Trends in Engineering, Mechanics and Computation* (2010) 101.

[6] Australian Building Codes Board, *Structural Reliability Handbook* (2015) 7.

components and connections when the calculated annual structural reliability index, for each action, is not less than specified values. For a building or structure of normal importance (importance level 2), the minimum annual structural reliability index is required to be:

- 3.8 for permanent and imposed actions, and
- 3.4 for wind, earthquake and snow actions.[7]

These target structural reliability indices have been set as the averages of the reliability indices found in current design Standards for steel, concrete and timber. There is a mathematical relationship between the structural reliability index and the probability of failure. Applying this mathematical relationship shows that the assumed annual probability of failure of primary structural components of structures of importance level 2 in Australia is:

- .00007 for permanent and imposed actions, and
- .0003 for wind, earthquake and snow actions.

The mathematical model for the reliability index takes actions and resistances, and represents these as random variables in probabilistic models. That is, actions and resistances are assumed to have a range of possible values that can be represented by distribution curves, in this case assumed to be lognormal distributions.

To calculate the reliability index, a resistance model must be created and used with models for the various actions to which the component or connection will be subjected. The models for actions represent typical characteristics of the actions as related to Australian conditions, but not specific to a particular location or a type of occupancy.[8]

As the resistance is a random variable, the resistance model must account for all sources of uncertainties in the determination of the resistance of a structural component or connection. The starting point is to determine the standard specified resistance. This is usually established by identifying the main parameters that affect the behaviour of the component, and constructing appropriate structural models to account for their effects. It must be formulated using five percentile characteristic material properties.[9]

The calculated resistance is related to the standard specified resistance (which is a deterministic value) by a number of factors. These factors account for the uncertainties in the assessment of the resistance, and are random values that are assumed to be statistically independent. The sources of uncertainties must include, but are not limited to the following:

[7] Australian Building Codes Board, *National Construction Code 2016 Volume 1 Building Code of Australia Class 2 to Class 9 Buildings*, sBV1.
[8] Australian Building Codes Board, *Structural Reliability Handbook* (2015) 11.
[9] Australian Building Codes Board, *Structural Reliability Handbook* (2016) 16.

- variability in mechanical properties of the materials (usually obtained from test data used for quality control of the material manufacturing process),
- variation in dimensions as the result of fabrication or construction processes (usually obtained from the established allowable tolerance and measurement of the dimensions of the compound), and
- uncertainties in the structural modelling of the component (usually obtained from the test research data used in the construction of the structural model).[10]

This method of calculating the structural reliability index provides a scientific way of establishing the appropriate design parameters for new or innovative structural products for which there are no standard specifications, or deemed to satisfy provisions. As the target values for the structural reliability index are set at the average values of those found in current practice using steel, concrete, timber, the public can have confidence that rational criteria are being applied to justify acceptance of new or innovative products, and that their probability of failure is no greater than the traditional and widely used products.

The use of a structural reliability index is provided for in the Australian National Construction Code,[11] and is the basis for structural design in many international Standards.[12]

LIMIT STATE DESIGN

Modern structures in many countries are designed using the current state of the art such that they are expected to withstand certain defined limit states. The **ultimate limit state** (**ULS**) is associated with collapse or other similar forms of structural failure. The **serviceability limit state** (**SLS**) is the state that corresponds to conditions beyond which specified service criteria for a structure are no longer met. These criteria are based on the intended use and may include limits on deformation, vibratory response, degradation or other physical aspects.[13]

The procedure for ULS design of a structure involves the following steps:

- Determine the importance level for the structure and the associated annual probability of exceedance for the applied environmental loads (wind, snow, ice and earthquake).
- Determine the ultimate permanent and imposed loads.

[10] Australian Building Codes Board, *Structural Reliability Handbook* (2016) 16, 17.

[11] Australian Building Codes Board, *National Construction Code 2016 Volume 1 Building Code of Australia Class 2 to Class 9 Buildings*, sBV1; Australian Building Codes Board, *National Construction Code 2016 Volume 2 Building Code of Australia Class 1 and Class 10 Buildings*, sV2.1.1.

[12] E.g., EN-1990:2002+A1 Eurocode – Basis of Design is the basis of structural Standards in Europe.

[13] Australian Standard AS1170.0:2002 Structural design actions Part 0: General Principles.

- Determine the ultimate environmental loads.
- Determine the ultimate values of any other applied loads such as liquid pressure, ground water, rain water ponding or earth pressure.
- Determine combinations of actions.
- Analyse the structure and its parts for the relevant combinations of actions.
- Design and detail the structure for robustness and earthquake.
- Determine the design resistance of the structural elements (the physically distinguishable parts of the structure, such as walls, columns, beams and connections) using the applicable Standards.
- Confirm that the design resistance exceeds the appropriate action effects.[14]

The basis of ULS is a recognition that the design parameters are inherently variable, and that the values adopted for design of the ultimate strength of a structure may be exceeded. It is generally obvious that the construction cost of a structure designed for higher loads or more conservative assumptions of material strength will be more than for a structure designed for lower loads or less conservative assumptions. That is, there is a trade-off between increased safety (a lower probability of failure) and cost.

This trade-off is brought into sharp focus in respect of strengthening of masonry buildings in New Zealand to resist earthquake loads. It is well known that such buildings are subject to catastrophic collapse in earthquakes, and that strengthening them to enhance earthquake resistance is expensive and may not prevent failure in extreme events. Where such buildings are required to be strengthened (e.g. where the occupancy class has changed), the regulations only require strengthening to 34% of the current earthquake design loads. Presumably this 34% limitation was selected on the basis of the unacceptable community cost of adopting a higher figure. As was known, such strengthening was inadequate to prevent collapse in a "design" earthquake. The 2010 and 2011 Canterbury earthquakes in fact imposed loads of the order of or higher than those specified by the Standard, with tragic consequences.[15]

Thus, implicit in the setting of design loads in Standards is a recognition of the cost implications. The consensus procedure involved in writing Standards suggests that design parameters are set at values that involve an acceptable level of risk at a cost the community is prepared to accept (at least in the view of the Standard writers). But it is important to recognise the obverse of the acceptable level of risk – there is a probability (small, but not zero), that a properly designed structure will fail, perhaps because of a combination of loads exceeding the design value and the materials not reaching their expected strength.

[14] Australian Standard AS1170.0:2002 Structural design actions Part 0: General Principles, s2.2.

[15] Donald Charrett, "The Canterbury Earthquakes – Lessons for Construction Lawyers" (2013) 8(2) *Construction Law International* 36.

The ULS design process makes such probabilities overt. Design loads are set with an annual probability of exceedance, selected with regard to the importance of the structure, the type of load and the design working life. Thus an ordinary structure with a design working life of 50 years whose failure has medium consequences for loss of human life, is required to be designed for an annual probability of exceedance of 1/500 for wind and earthquake loads. However, a structure with post-disaster functions with a design working life of 100 years, is required to be designed for an annual probability of exceedance of 1/2500 for wind and earthquake loads.[16]

The procedure for SLS design of a structure involves the following steps:

- Determine the type of serviceability conditions to be considered for the whole structure and its individual elements.
- Determine the serviceability load event and serviceability limits for the design serviceability condition being considered.
- Determine the permanent loads and serviceability imposed loads.
- Determine serviceability loads for wind, snow and ice.
- Determine the serviceability values of any other applied loads such as liquid pressure, ground water, rain water ponding or earth pressure.
- Determine applicable combinations of actions.
- Analyse the serviceability response of the structure and its parts for the relevant combinations of actions for each serviceability condition.
- Determine the serviceability response.
- Confirm that the serviceability response does not exceed the appropriate limiting values for each of the serviceability conditions identified.[17]

The significance of SLS and ULS design are illustrated by their application in the design of buildings in NZ to resist earthquakes:

> The SLS involves designing the building so it remains fit for use in the event of an earthquake with a magnitude of shaking that may be expected to occur once or twice during the design life of the building. If damaged in such an event it should be repairable at low cost.
>
> For the ULS the design criteria have been developed to ensure that life is protected in the event of a major earthquake. This is achieved by requiring the building to have suitable levels of strength, stiffness and ductility to survive a major earthquake without collapsing as a result of structural failure. For commercial buildings of normal importance this major earthquake is assumed to have a return period of 500 years. Post disaster structures, structures that are designed to contain significant numbers of people, and school buildings are designed for earthquake actions with return periods of 2500 and 1000 year respectively (assuming a building life of 50 years). Satisfying the design criteria for the ULS should enable building to be repaired after earthquakes

[16] Australian Standard AS1170.0:2002 Structural design actions Part 0: General Principles, s2.2.
[17] Australian Standard AS1170.0:2002 Structural design actions Part 0: General Principles, s2.3.

> that are more intense than those envisaged for the SLS. However, the ULS design criteria do not imply that repairs are possible after a ULS earthquake.[18]

Thus, for NZ commercial buildings of normal importance with a design life of 50 years, the annual probability of exceedence for earthquake ULS is 0.2% (1/500), whereas the annual probability of exceedence for earthquake SLS is 4% (1/25).

ROBUSTNESS

Structures are designed to withstand normal loads and actions over their service life. This includes design so that facilities remain operational under operating or serviceability loads (SLS design), and so that the structure does not fail under loads less than the ultimate design loads (ULS design).

However, abnormal events can occur that are unexpected and unpredictable, such as fire, explosion, impact, consequences of human errors or loads in excess of the design loads. The consequences of such events were drawn to the attention of structural engineers by the partial collapse of the 22-storey Ronan Point apartment building in East London in 1968. Following a gas explosion, one corner of the building collapsed killing four people.

The subsequent inquiry noted the importance of guarding against progressive collapse in the following terms:

> "The extent of the collapse subsequent to the explosion was inherent in the design of the building. The collapse has exposed a weakness in the design. It is a weakness against which it never occurred to the designers of this building that they should guard. They designed a building which they considered safe for all normal uses; they did not take into account the abnormal. They never addressed their minds to the question of what would happen if for any reason one or more of the load bearing members should fail. … The designers of Ronan Point were not alone in the attitude they adopted; it is significant that we have not been referred to any English publication which has drawn attention to the need to think of tall system buildings as civil engineering structures requiring alternate paths to support the load in the event of the failure of a load bearing member. It appears to us that there has been a blind spot among many of those concerned with this type of construction and it would be wrong to place the blame for the failure to appreciate the risk of progressive collapse upon the shoulders of the designers of this building alone. They fell victims, along with others, to the belief that if the building complied with existing building regulations and Codes of Practice it must be deemed to be safe. Experience has shown otherwise."[19]

The progressive collapse of Ronan Point focussed structural engineer's attention on the importance of designing robustness into a structure, so that it has capacity to withstand abnormal loads. In the years since the collapse

[18] NZ, Canterbury Earthquakes Royal Commission, *Final Report Volume 1* (2012) 54.

[19] Great Britain, Ministry of Housing and Local Government, Collapse of Flats at Ronan Point Canning Town (1968), 4.

of Ronan Point, the importance of such design has been reemphasised by terrorist attacks which have resulted in the collapse of major buildings such as the World Trade Centre[20] and the Federal Building in Oklahoma. In the Oklahoma Federal Building, whilst only 4% of the building was destroyed by the bomb blast, a further 38% was subsequently destroyed by progressive collapse.[21]

Thus, in addition to the requirements for ULS and SLS design of a structure, it is now a requirement that the design exhibit **structural robustness**: the ability of a structure to withstand events like fire, impact or consequences of human errors, without being damaged to an extent disproportionate to the original cause.[22] Robustness is achieved by detailing structures such that all parts of the structure are tied together both in the horizontal and the vertical planes so that the structure can withstand an abnormal event without being damaged by an event disproportionate to that event.[23]

In a recent addition to the Australian National Construction Code, compliance with the structural performance requirements for a building or structure is verified for structural robustness by:

> "(a) assessment of the structure such that upon the notional removal in isolation of:
> (i) any supporting column; or
> (ii) any beam supporting one or more columns; or
> (iii) any segment of a load-bearing wall of length equal to the height of the wall, the building remains stable and the resulting collapse does not extend further than the immediate adjacent storeys; and
> (b) demonstrating that if a supporting structural component is relied upon to carry more than 25% of the total structure a systematic risk assessment of the building is undertaken and critical high risk components are identified and designed to cope with the identified hazards or protective measures chosen to minimise the risk."[24]

Other design aspects that can enhance a structure's robustness are redundancy and ductility. **Redundancy** is achieved by having multiple load paths that can transmit forces to the ground where they are resisted. Thus, if one load path is destroyed, e.g. by failure of one load carrying member, the forces in that member can be conveyed to the ground by an alternate load path. The importance of redundancy was highlighted by the behaviour of the Hotel Grand Chancellor in the Christchurch earthquake. This building suffered complete failure of a shear wall during the 2011 earthquake. Although that failure came close to causing a catastrophic collapse of the

[20] http://wtc.nist.gov/media/Sunder_Progressive%20Collapse_Remarks_050106.pdf (Last accessed 23 November 2016).

[21] http://www.bfrl.nist.gov/861/861pubs/collapse/workshop/5.WorkshopSlides(Murrah%20Bldg).pdf (Last accessed 23 November 2016).

[22] Australian Standard AS1170.0:2002 Structural design actions Part 0: General Principles, s1.4.21.

[23] Australian Standard AS1170.0:2002 Structural design actions Part 0: General Principles, s6.1.

[24] Australian Building Codes Board, *National Construction Code Volume 1 Building Code of Australia Class 2 to Class 9 Buildings* (2016) 75.

27-storey building, there was sufficient redundancy and resilience within the overall structure to redistribute load from the failing element and to halt the collapse.[25]

Ductile behaviour (**ductility**) of a member or connection is the ability to deform without losing strength above the point where the member or connection is unable to sustain increased load. Brittle behaviour is the opposite to ductile behaviour – a member fails in a brittle manner when it fails completely and is unable to sustain any load once its maximum load strength is reached. Unreinforced concrete and cast iron fail in a brittle manner under tension, and are therefore unsuitable for use in applications such as beams where they are required to withstand tension.

Ductile behaviour is particularly important in structures that are required to withstand earthquake loads. The modern approach to earthquake resistant design is to build ductility into the structure so that it has the capacity to undergo repeated deformation whilst dissipating substantial energy through the deformations of the structure. Steel and properly designed reinforced concrete are inherently ductile materials; unreinforced masonry (brick and stone) is not. A well-designed ductile structure to modern standards will be able to withstand moderate earthquakes without significant structural damage, and a severe earthquake even greater than the "design earthquake" with substantial damage, but without collapsing. Such a damaged building may need to be demolished after the earthquake, but it will have performed its most important function of protecting the lives of its occupants.

> "Protection against collapse in most modern buildings is provided by ensuring that in the event of a major earthquake the structure will behave in a ductile manner. This involves cracking of concrete and yielding of reinforcement in reinforced concrete buildings and yielding of structural steel members in steel buildings. This causes damage to structural elements as well as damage to non-structural elements such as the linings in the building. A consequence of this is that protection against collapse and protection of life may be at the expense of the building, which may have to be demolished after the earthquake."[26]

The Canterbury Royal Commission identified a number of major advantages of designing a structure so that it behaves in a ductile manner in a major earthquake:

1. Lower strengths are required, reducing in construction cost.
2. There is more freedom in the architecture of the building, enabling greater clear floor spans to be used with smaller beams, increased spacing of columns, etc.
3. A ductile building is tough in an earthquake and can generally withstand earthquakes considerably greater than design level (ULS) without collapse.
4. A ductile structure generally gives warning well before collapse occurs by opening up wide cracks in reinforced concrete structures and sustaining high displacements in steel and concrete members.

[25] NZ, Canterbury Earthquakes Royal Commission, *Final Report Volume 2* (2012) s3.
[26] NZ, Canterbury Earthquakes Royal Commission, *Final Report Volume 1* (2012) 55.

5. Non-ductile buildings give no warning of collapse and generally have less reserve capacity to sustain earthquakes greater than design level without collapse."[27]

SERVICE LIFE

In this paper, the **service life** of a facility is defined as the period of time that it is in functional operation.

The service life of a facility is of fundamental importance to the long term owner of that facility, since it is required to deliver an economic return over that service life. Further, the facility may have to be replaced when it is no longer functional. Long term facility owners are usually interested in long service lives, subject always to the economics of procurement and available funding. A rational decision of the required service life would be based on a determination based on the minimum net present value:

> "Fenwick and Rotolone (2003) explored the economics of service life for civil infrastructure from a long term asset owner's perspective. They adopted the AASHTO (2006) definition of service life as the period of time that the structure is expected to be in operation, and considered a simple example of a culvert, exploring service lives between 30 and 300 years. For almost all cases over a range of feasible interest rates, a service life of 300 years before replacement proved to be the most economical outcome on a net present value basis."[28]

The determination of the optimum service life of a facility also needs to consider the operational costs:

> "In targeting a service life performance for a structure, the asset owner needs to be aware not only of the initial cost of creating the structure, but its service life and the long term cost of maintaining and repairing it over that service life, and finally its replacement cost."[29]

Facilities designed today typically have an **expected service life**, although only time will tell whether a particular facility ultimately achieves its expected service life. Standards are often explicitly or implicitly based on an expected service life. It is doubtful that the issue of expected service life was overtly considered or addressed in the past. For example, did the designers or funders of the Brooklyn bridge over the East river in New York contemplate or require that this bridge would be carrying traffic over 130 years after it was opened?

[27] NZ, Canterbury Earthquakes Royal Commission, *Final Report Volume 1* (2012) 58.

[28] John Connal & Marita Berndt, "Sustainable Bridges – 300 Year Design Life for Second Gateway Bridge" http://www.outokumpu.com/SiteCollectionDocuments/Research-paper-Susstainable%20Bridges.pdf (Last accessed 23 November 2016).

[29] John Connal & Marita Berndt, "Sustainable Bridges – 300 Year Design Life for Second Gateway Bridge" http://www.outokumpu.com/SiteCollectionDocuments/Research-paper-Susstainable%20Bridges.pdf (Last accessed 23 November 2016).

The **required service life** of a facility is the service life desired by the owner. It is one of the objectives of the design process, and will usually coincide with the design life:

> "A service life performance must be formulated into specific design criteria to provide the designer with objectives for the design which are then encapsulated in specification requirements that must be met by the builder during the construction. The codes usually define a design life that implies a particular service life regarded by society as acceptable. For example, AS5100 (2004)[30] adopts a design life of 100 years. BS5400.1 (1988)[31] assumes a design life of 120 years and AASHTO[32] (2006) is based on a design life of 75 years. It is usual to simply apply these codes and standards that imply a particular assumption of service life performance. These are based on current materials and technologies and perhaps inhibit achieving very long service lives through the use of new materials or combinations of materials and new technologies."[33] [citations added]

However, the required service life is ultimately the choice (explicit or implicit) of the sponsor (or funder) of a project. A service life in excess of the norm can be required by an explicit specification of design life in the relevant contract. For example, the second Gateway Bridge over the Brisbane River in Brisbane, Australia was required to have a design life of 300 years, a world first and far in excess of the typical 50–100-year design life of infrastructure in Australia. This far sighted decision was taken by Queensland Motorways in the knowledge that the long term benefits would far outweigh the immediate cost. In the event, the actual premium was small. Using existing, known technology, the required changes to "normal" design and construction involved minor design and construction changes such as: the use of galvanised reinforcement in some areas, increased cover to reinforcement, design of the concrete mix, and an unrelenting focus on the constructed quality of the concrete, focussing on the well-known issues of the three C's: cover, compaction and curing.

DESIGN LIFE

For the purposes of this paper, **design life** can be defined as the **expected service life** that results from the design process. Australian Standard AS1170.0:2002[34] defines **design working life** as:

[30] Australian Standard for Bridge Design.
[31] British Standard code of practice for the design and construction of steel, concrete and composite bridges – General Statement.
[32] American Association of State Highway and Transportation Officials.
[33] John Connal & Marita Berndt, "Sustainable Bridges – 300 Year Design Life for Second Gateway Bridge" http://www.outokumpu.com/SiteCollectionDocuments/Research-paper-Susstainable%20 Bridges.pdf (Last accessed 23 November 2016).
[34] Structural design actions Part 0: General Principles.

> "Duration of the period during which a structural element, when designed, is assumed to perform for its intended purpose with expected maintenance but without major structural repair being necessary.
>
> NOTE: In the context of this Standard, the design working life is a 'reference period' usually stated in years. It is a concept that can be used to select the probability of exceedance of different actions [sets of concentrated or distributed forces acting on a structure (direct action) or deformation imposed on a structure or constrained within (indirect action)]."

The following example is the specified requirement in a design specification for the design life of sewerage lagoons:

> "All equipment shall be designed and constructed to have a working life of at least 15 years, working 24 hours a day, 365 days per year. Valves and pipework shall be designed and constructed of materials that shall have a design life of 30 years. Structures such as concrete and steel shall be designed and constructed of materials that have a design life of 50 years and be maintenance free for 50 years."[35]

As indicated above, the design life is an outcome of the design process that takes into account a range of relevant factors such as prevailing environmental conditions, durability, operational parameters and material behaviour. The design life for normal structures in Australia is generally taken as 50 years.

The following summarises the process adopted to achieve a design life of 300 years for the Second Gateway Bridge over the Brisbane river:

> "The durability design process for extended life requires the specific analysis of the environmental conditions in which the structure is placed, the strategic use of a range of materials and an understanding of the means by which they deteriorate and the rate of that deterioration.
>
> …
>
> The process takes a first-principles and deterministic approach to modelling the environmental influences and material performance, but rather than just adopting mean values of the governing parameters, it overlays an understanding or assumption of their variation using known or assumed coefficients of variation to account for the stochastic nature of the deterioration process.
>
> …
>
> The project scope and technical requirements (PSTR) for the bridge specified that the durability be applied diligently and continuously throughout the process of design, construction and throughout the maintenance period, and that the Second Gateway Bridge have a design life of 300 years, with some replaceable sub-items having design lives ranging from 20 years (wearing course) to 100 years (bearings). Design life was defined as the period assumed in design for which the structure or structural element is required to perform its intended purpose without replacement or major structural repairs."[36]

[35] *CH2M Hill v New South Wales* [2012] NSWSC 963; (2014) 30 BCL 35, paragraph 99.

[36] John Connal & Marita Berndt, "Sustainable Bridges – 300 Year Design Life for Second Gateway Bridge" http://www.outokumpu.com/SiteCollectionDocuments/Research-paper-Susstainable%20Bridges.pdf (Last accessed 23 November 2016).

A CASE STUDY ON DESIGN LIFE AND SERVICE LIFE

The distinction between design life and service life was brought into sharp focus in the case of *Mt Højgaard A/S v E.ON Climate and Renewables UK Robin Rigg East Ltd*. The project was a design and construct contract for a wind farm offshore of Scotland, the contractor being Mt Højgaard A/S and the Employer E.ON Climate and Renewables UK Robin Rigg East Ltd.

The litigation in this case arose from the failure of the grouted connections between piled foundations and the towers supporting the wind turbines. The grouted connections were designed to accepted international Standards and verified by the independent certifying authority of Det Norske Veritas (**DNV**). There was no negligence in the design of the grouted connections.

The Technical Requirements (**TR**) that formed part of the contract stated that: "*The design of the foundations shall ensure a lifetime of 20 years in every respect without planned replacement*." At first instance, the Judge found this was a contractual obligation and that the Contractor was liable for the financial consequences of a failure to achieve the required 20-year service life, evidenced by the failure of the grouted connections before 20 years had elapsed.[37]

The grouted connections were designed for a design life of 20 years in accordance with the prevailing "state of the art" as detailed in the specified international standard. However, there was a serious (and unknown at the time) error in the DNV Standard for the design of the grouted connections.

In addition to the requirement for the facility to be designed for a life of 20 years, the judge found that the specified service life of 20 years was also a contractual obligation. Thus, even though the connection had a design life of 20 years in accordance with the "state of the art" (the accepted DNV Standard), failure to achieve the required service life was found to be a breach of contract.

On appeal, the Court of Appeal had a different view on the contractual obligations in relation to the design:

> "89. The starting point must be consideration of TR paragraph 3.2.2.2 (2). ['The design of the foundations shall ensure a lifetime of 20 years in every aspect without planned replacement. The choice of structure, materials, corrosion protection system operation and inspection programme shall be made accordingly.'] This is the provision which was critical to the judge's decision.
>
> 90. That paragraph undoubtedly says that the foundation design shall ensure a lifetime of 20 years. At first sight, such a provision, if incorporated into the contract, is a warranty that the foundations will function for 20 years.
>
> 91. On the other hand, all of the other provisions in the TR are directed towards a design life. If a structure has a design life of 20 years, that does not mean that

[37] *MT Højgaard A/S v E.ON Climate and Renewables UK Robin Rigg East Ltd and E.ON Climate and Renewables UK Robin Rigg West Ltd* [2014] EWHC 1088 (TCC); [2014] BLR 450.

inevitably it will function for 20 years, although it probably will. As noted in Part 2 above, the TR contain many references to the requirement for the foundations to have a design life of 20 years. See, for example, TR paragraphs 1.6 and 3.2.6.

[1.6 'The Wind Farms are to be designed, constructed and operated to provide the lowest lifetime cost option capable of meeting the full requirements of this Specification. Maximum output with minimum maintenance and maximum availability to generate are the prime requirements of the scheme.

…

The Works, together with the interfaces detailed in Section 8, shall be designed to withstand the full range of operational and environmental conditions with minimal maintenance. The Works elements shall be designed for a minimum site specific "design life" of twenty (20) years without major retrofits or refurbishments; all elements shall be designed to operate safely and reliably in the environmental conditions that exist on the site for at least this lifetime.'

3.2.6 "All parts of the Works, except wear parts and consumables shall be designed for a minimum service
life of 20 years. …]

…

98. In fact the obligations imposed by clause 8 are the opposite of requiring an absolute warranty of quality. What they require is due care, professional skill, adherence to good industry practice, compliance with the Employer's Requirements and so forth.

…

101. Clause 8.1 (x) requires that the works as a whole shall be 'fit for purpose'. Those words are qualified, however, by the phrase 'as determined in accordance with the Specification using Good Industry Practice'."[38]

Jackson LJ clearly articulated the distinction between design life and service life:

> "If a structure has a design life of 20 years, that does not mean that inevitably it will function for 20 years, although it probably will."[39]

These two judgments of judges experienced in construction law highlights the difficulties faced by designers in construing their contractual obligations. One judge determined that achievement of a specified service life was a contractual obligation, and failure to achieve that (without negligence), was a breach of contract. Conversely, the Court of Appeal found, based on a detailed legal construction of the terms of the contract, that the Technical Requirements (fourth in the hierarchy of contract documents) did not warrant that the foundations would have a service life of 20 years. The Court of Appeal found that the obligations imposed by the conditions of contract were the opposite of requiring an absolute warranty of quality: due care, professional skill, adherence to good industry practice, compliance with the Employer's Requirements etc.

However, designers cannot draw much comfort from the Court of Appeal's decision:

[38] *Mt Højgaard A/S v E.ON Climate and Renewables UK Robin Rigg East Ltd* (CA) [2015] EWCA Civ 407; [2015] BLR 431.

[39] *Mt Højgaard A/S v E.ON Climate and Renewables UK Robin Rigg East Ltd* (CA) [2015] EWCA Civ 407; [2015] BLR 431, paragraph 88.

- It was derived from a close legal analysis of the specific words of "*contractual documents of multiple authorship, which contain much loose wording*", construing their meaning in accordance with conventional legal analysis.
- It differed from the conclusion of the Judge at first instance, illustrating that the correct legal analysis was not obvious.
- It highlighted that if a contract is worded with sufficient clarity, it can impose a double obligation on the contractor:
  - to comply with particular specifications and standards, and
  - to achieve a particular result.

In a salutary reminder to designers and contractors of the importance of understanding the contractual obligations they undertake, Jackson LJ noted:

> "It is not unknown for construction contracts to require the contractor (a) to comply with particular specifications and standards and (b) to achieve a particular result. Such a contract, if worded with sufficient clarity, may impose a double obligation upon the contractor. He must as a minimum comply with the relevant specifications and standards. He must also take such further steps as are necessary to ensure that he achieves the specified result. In other words, he must ensure that the finished structure conforms with that which he has warranted. As Mr Marrin points out, the design and build agreement in *Independent Broadcasting Authority v EMI Electronics Ltd* (1980) 14 BLR 1 was a contract of that character."[40]

FITNESS FOR PURPOSE

The common law duty of care owed by a professional to exercise the due skill and care of an ordinarily competent member of the profession (also implied into contracts for design) is not a guarantee of success:

> "… if you employ (an architect) about a novel thing, about which he has little experience, if it has not had the test of experience, failure may be consistent with skill. The history of all great improvements shows failure of those who embark in them."[41]

In other words, a designer is not automatically providing a warranty that the design will be fit for purpose. However, the situation may be different in the case of a design and construct contract:

> "But, in the absence of a clear, contractual indication to the contrary, I see no reason why one who in the course of his business contracts to design, supply, and erect a television aerial mast is not under an obligation to ensure that it is reasonably fit for the purpose which he knows it is intended to be used."[42]

[40] *Mt Højgaard A/S v E.ON Climate and Renewables UK Robin Rigg East Ltd* (CA) [2015] EWCA Civ 407; [2015] BLR 431, paragraph 79.

[41] *Turner v Garland and Christopher* (1853) Hudson's Building Contracts (4th Edition) Vol II, 1.

[42] *Independent Broadcasting Authority v EMI Electronics Ltd and BICC Construction Ltd* (1980) 14 BLR 1, 47 per Lord Scarman.

Arguably, fitness for purpose is an implied term of a design and construct contract, absent clear words to the contrary. In the *Mt Højgaard* Court of Appeal case discussed above, Jackson LJ found sufficiently clear words in the contract to define the designer's obligation as the exercise of due skill and care, and not fitness for purpose. The issue will always ultimately depend on construction of the contract, as highlighted by Jackson LJ's careful analysis in the *Mt Højgaard* case.

Notwithstanding that the terms of a contract may impose the additional requirement that a design must be fit for purpose, judges will circumscribe that obligation by requiring that the purpose must be made known to the contractor, and "fit for purpose" will be limited to reasonably fit for purpose having regard to reasonably expected conditions. Further, fit for purpose obligations may not apply to the extent that the employer has not relied on the contractor's expertise.

The following statements indicate the limitations on the fitness for purpose of the design for lagoons at a sewerage treatment plant. In this case, the designer accepted that there would be at least an implied term of the design contract that the design to be provided pursuant to it would be fit for the purposes that it was required to serve, as those purposes had been made known to the designer.

> "I repeat that [the designer] was not obliged to provide a design that took account of, and guarded against, all possibilities of harm, no matter how remote. Its obligation was to provide what might be summarized as cost effective solutions that would achieve the design objectives – including of course, a 50-year maintenance free service life for the lagoons. As [the lead designer] in effect said, that requires an assessment of the remoteness of the risk."[43]
>
> "It cannot be suggested that [the designers] were obliged to provide a design that guarded against every risk, no matter how remote the risk and how expensive the prevention of its guard. Its obligations included the provision of 'effective, efficient and economical solutions to satisfy the performance objectives and other requirements set out in the Brief'. In pursuit of that obligation, [the designer] was obliged 'to provide details of alternative proposals that satisfied these objectives and requirements'. (In each case, the quotation comes from cl 8.1 of the general conditions forming part of the design contract.)"[44]

CONCLUSION

This paper has endeavoured to explain some of the engineering issues involved in the design of civil engineering structures. Notwithstanding the known "state of the art", the knowledge of the behaviour of materials and the enormous computational power available to designers, there is still considerable art complementing the science in structural design.

[43] *CH2M Hill v New South Wales* [2012] NSWSC 963; (2014) 30 BCL 35, paragraph 330.
[44] *CH2M Hill v New South Wales* [2012] NSWSC 963; (2014) 30 BCL 35, paragraph 319.

The application of that art and science means that properly designed structures to modern standards usually perform their function as intended over their working life.

However, modern ULS design explicitly recognises that there is a probability (albeit small) that a design prepared with due skill and care may fail during its service life. That is, the actual service life does not achieve the design life.

In such a situation, the legal consequences will usually depend on the terms of the contract. Absent a contractual term that the designer warrants that the design will be fit for purpose, the common law limits the designer's liability to any failure to exercise due skill and care. However, it is clear that in an appropriately worded contract, the designer may warrant that the design will be fit for purpose and the service life will be achieved. In such a case, the designer will be liable for the consequences of breach of contract if the service life is not achieved, irrespective of any fault on the part of the designer.

It is common for construction contracts to consist of a large number of complex legal and technical documents, authored by a number of lawyers and engineers. As the *Højgaard* case illustrated, construing the terms of a such a construction contract where there are conflicting requirements may not be an easy task, and the outcome may not be obvious even to experienced lawyers.