Bridge Failures and Lessons Learnt

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Bridge Failures and Lessons Learnt

Future-proofing to prevent disasters

Richard Fish

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Foreword

As the current chair of the UK Bridges Board, I am delighted to have been asked by Richard to write the foreword to his book on bridge collapses. A hugely important subject, but often dismissed as something that only happens elsewhere in the world, this book brings to the fore the reasons why collapses happen and the precursor events that can indicate problems in the making.

I, like Richard in his former roles, am a custodian of ageing highway structures. The conflicting pressures of keeping the network open and available whilst undertaking essential, safety-critical maintenance does not get any easier and Richard is hugely experienced in balancing the technical, budgetary, customer and political demands that are placed upon bridge managers. In his current role as Technical Secretary of the Bridge Owners Forum (the research arm of the UK Bridges Board), Richard regularly reports on collapses and precursor events around the world and has given numerous presentations to the industry on the subject. He has also been instrumental in forging UK Bridges Board and Bridge Owners Forum links with CROSS (Collaborative Reporting for Safer Structures) and is exploring how the learning from UK precursor events and collapses can be shared with the wider bridge community.

Many authorities no longer have the breadth and depth of experienced bridge engineers in their employ to inspect, manage and maintain their bridge stock, yet are expected to do just that. With difficult investment decisions to be made, asset owners are under pressure to do more with less, be that to carry ever-increasing loads, reduce material use, minimise carbon and keep bridges in service for as long as possible. However, without regular maintenance to structures, this cannot go on indefinitely without restrictions or, in the worst case, a significant failure.

Precursors in the form of element failures happen regularly, a source of frustration to the public by causing inconvenient traffic disruption while a bridge joint is ‘fixed’ during rush hour, for example. However, often these unplanned repairs are only a sticking plaster until a larger maintenance scheme can be implemented with the underlying repair not able to be completed in an overnight possession and patched up as best as possible to allow the road to reopen. Until a permanent repair can be undertaken, joints will continue to leak, unseen concrete or steel below will continue to deteriorate and potholes will continue to form in the carriageway above the deck. These precursor events are often an indication of something that will require both significant investment and time to put right, work that should have been completed at the optimum intervention point and not left to an emergency repair.

Asset management champions the importance of understanding the condition of an asset and intervening at the optimum point to minimise whole-life cost and unplanned disruption. Of course, this makes perfect sense. However, for publicly funded asset owners, this isn't always as easy as it sounds. For bridges, it is only recently that competency-based inspector qualifications have become available, following the UK Bridges Board lead to instigate the development of such a scheme. Good-quality condition data is only the first crucial part of the story, however. In the book, Richard discusses bridge condition, the knowledge required of inspectors, engineers and managers, the many risk-based decisions that need to follow promptly and the trust that needs to be engendered with decision makers to ensure sufficient priority is given to implement essential maintenance, repair and renewal of our ageing infrastructure and ensure public safety. If decision processes are not followed through to their conclusion, there is a significant risk of element or structural failure. No bridge manager wants this to occur on 'their watch'.

Knowing when an asset will fail is not an exact science. Our models contain assumptions; the loads, the materials, the condition and the structural behaviour are all approximations. However, bridge engineers are best placed to advise on the risks when they are in possession of all the facts and can use their engineering judgement and expertise to come to an informed decision. This is where knowledge of previous failures, as set out in this book, is invaluable. Knowing where to start looking for that needle in the haystack of a network of competing priorities is essential.

To my knowledge, there is no definitive guide to bridge failures. There are many excellent reports on individual bridge collapses or failures of infrastructure, such as in the USA and Royal Commission reports on box-girder failures in the 1970s. Significant improvements were made following these latter failures with the introduction of Technical Approval and the requirement for independent checking, depending on the complexity of the structures. Technical approval and independent checking are now taken for granted in new construction but what about managing the current stock and keeping it in safe service? The number of existing structures far outweighs the number of new structures built in any year so how do we ensure that lessons are learnt when things go wrong?

This book, in my opinion, is long overdue and is essential in highlighting the criticality of bridges and the risks that we, as a society, take in using the infrastructure we implicitly rely upon. To fully understand the risks and to give opportunities to learn from others, the book sets out case studies, as well as discussing knowledge sharing, condition, vulnerable details, climate change and ethics; these are all crucial factors that bridge managers must consider in order to effectively communicate the risks to their senior managers and ultimately the political masters who decide how our valuable resources should be spent.

Richard is the perfect author for this book as a highly respected member of the UK and international bridge engineering community and commentator on bridge failures worldwide. I would like to personally thank him for his support to the UK Bridges Board, the Bridge Owners Forum and to myself over the years. Read and learn from this excellent book; I know I will.

Dr Hazel A McDonald BEng (Hons), PhD, CEng, FICE
Chief Bridge Engineer (Head of Structures), Transport Scotland
Chair of the UK Bridges Board

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Preface

Bridges of all ages, structural forms and spans are vital elements in our transportation networks across the globe. They carry every imaginable mode of transport, from high-speed railways to leisurely footpaths and cycleways. And, for the most part, they function as their designers had intended; as long as they are regularly inspected and appropriately maintained.

It is impossible to put a number on the world's bridge population with any degree of accuracy, but it will be at least in the tens of millions. As far as the travelling public is concerned, the vast majority of these will be 'invisible'; it will also be taken for granted that everyone crossing over, or passing under, those bridges will be safe and free from risk. They will have an implicit trust in the designers and builders and those responsible for their maintenance and management. And this is exactly how things should be.

Very occasionally, however, for whatever reason, something goes wrong, and a bridge fails. And, although this will only apply to a tiny, almost infinitely small, percentage of the total number, the consequences are likely to be huge. That implicit trust will evaporate, communities will suffer, lives will be affected and, very sadly, in some cases they will be lost. It is a sobering thought that at the time of writing, since the turn of this century and across the world, well over 1200 people have been killed as a result of a bridge collapse.

For every bridge failure, there will be a reason; or more likely, multiple reasons. It is vital that those reasons are investigated and the knowledge shared, so that lessons can be learnt. For the most part, those lessons will be about bridge engineering, and engineers in all countries should be able to apply them in order to maintain that public trust and to keep their bridges safe. Occasionally, those investigations will find that human error has been a contributory factor. That could be anything from a simple mistake or oversight to incompetence or negligence. If the latter, this is literally criminal, and the relevant legal system should swing into action.

But even if an error was innocent and easily made, there should be no shoulder-shrugging; no 'act of God' argument. Professional engineers have an ethical obligation to serve society. Not only must they be responsible for their own actions and decisions but they must also act when they become aware of something their colleagues may, or may not, have been doing.

Although my career, in its various roles as a bridge engineer, has seen a handful of failures and a few more near misses, thankfully all have been of a minor nature, and none has resulted in injury. My interest in collapses has grown over the last 20 years or so but not in any morbid sense but rather with emotions of anger, frustration and exasperation that such things should happen.

Every engineer will have made mistakes, not least the author of these pages, but the message of learning and sharing has been part of our engineering DNA for millennia and must continue. And collective learning from mistakes is another essential principle of our profession.

One of my aims in writing this book is to aid that learning process, in terms of both engineering and ethics, by looking back at bridge failures not only historically but also in recent times. My other objective is to look forwards, to discuss what we should be doing to try to prevent collapses. It is my sincere hope that the book will make some contribution to ensuring that lessons continue to be learnt; and even, possibly, in helping to prevent a collapse; and perhaps even save a life.

Richard Fish
2024

Acknowledgements

There have been many people I have worked for, worked with and have had the pleasure to have managed who have helped me during my career, now scarily approaching the 50-year mark. Retirement beckons.

Although I could not possibly mention them all, I must acknowledge the inspiration given to me by the late Jolyon Gill (1951–2011). Working with Jolyon on the Tamar Bridge strengthening and widening was not only great fun but also occasionally a white-knuckle ride! It was Jolyon who fanned the flame of my passion for suspension bridges and later encouraged my transfer into the world of the one-man consultant, where he later joined me, and also where we collaborated on some interesting projects. A brilliant engineer, taken from us far too soon.

I would also like to acknowledge another long-serving colleague and friend, Graham Cole, a stalwart of the old County Surveyors' Society (CSS) Bridges Group and, latterly, another one-man consultant; we have worked on several projects together over the last decade or so, including co-editing *Highway Bridge Management* (ICE Publishing, 2022). I am very grateful for his kind offer to review my drafts and even more so for his constructive critique.

My thanks are also due to Dr Hazel McDonald for agreeing to write the foreword and to the Emerald Publishing editorial team, notably Cathy Sellars who guided me through the production process.

Lastly, my thanks go to my wife and family, who for reasons unknown to me, still don't get bridges.

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About the author

Richard Fish BSc, CEng, FICE, FIStructE, FCIHT, MIAM, FRSA

A graduate of Southampton University, Richard began the first part of his career in the public sector. In 1976, he joined Somerset County Council on its graduate training programme, qualifying as a Chartered Civil Engineer in 1980. Most of his time in Somerset was spent on bridge design and construction.

In 1989, he moved to Cornwall County Council as County Bridge Engineer. In 1991, he joined the County Surveyors' Society (CSS) Bridges Group, taking over as Secretary a year later and holding that position until 2000. From 1991 to 2000, he also chaired the South West Area Bridge Conference.

Still in Cornwall, in 2000 he was promoted to the post of Assistant County Surveyor. Less than two years later, he was promoted again to head what had been the old County Surveyor's Department to become Director of Planning, Transportation and Estates, one of only a few local authority bridge engineers to have reached that level. Remaining in this post until 2009, he was also Chairman of both the CSS Bridges Group and the UK Bridges Board from 2005 to 2009, maintaining his commitment to bridges.

Coinciding with a major reorganisation of local government in Cornwall, Richard left the public sector and established his own consultancy business in 2009, specialising in bridge asset management and long-span suspension bridges. The latter built on his experience as project manager of the award-winning Tamar Bridge strengthening and widening project between 1994 and 2001. Over the last 15 years, he has worked for well over 30 clients in the UK and overseas in countries such as the USA, New Zealand, Turkey and Malaysia. Since 2010, he has also been the Technical Secretary of the Bridge Owners Forum, a role which has enabled him to be an active member of the UK Bridges Board.

Richard's interest in bridge collapses has grown over the years, along with a recognition of the responsibility that the bridge engineering sector, especially decision makers, has to carry. He is now widely recognised as one of the UK's authorities on the subject.

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Chapter 1
Introduction

Bridge failures in the twenty-first century should be inexcusable and yet they still occur. No collapse can ever be considered as just one of those things (stuff happens), nor unforeseeable. Especially in the modern first world, bridges should be implicitly safe and free from any risk, at least as far as the travelling public is concerned. Collapses still happen, however, with increasing frequency. A trend which is almost certainly going to get worse before it gets better. The key issue is to learn from failure. 'Those who cannot remember the past are condemned to repeat it' (Parkinson, 1993, p. 266).

1.1. Definitions

Before delving into the subtle differences between collapse and failure, it is best to consider some definitions in the context of this book. A bridge collapse is total, after which the bridge is unusable. While a bridge failure may also result in the same outcome, a failure of an element may be anything from, for example, the need for an expansion joint replacement to an urgent closure of the structure. While the former can be fixed in a relatively short timescale, the latter may need a significant maintenance or strengthening intervention and will either be out of use, or restricted in terms of loading, for a considerable length of time. The other distinction between collapse and failure is that the former is sudden, catastrophic and often fatal. Failure, however, as defined above, can be managed, either reactively or proactively.

Another definition worth considering is that of risk. Risk management principles define risk as the product of likelihood and consequence, and by using a relatively coarse numbering system, attention can be focused on key risks while giving others a lower priority. Although risk can never be completely eliminated, risk practitioners use the acronym ALARP: as low as reasonably practicable. This is the level of risk at which there is a degree of comfort that everything that can be done is being done to keep those risks to a minimum. A more detailed discussion on all aspects of risk is given in Chapter 8.

It would be unfair, however, to expect a member of the travelling public to analyse risk in such a way. As will be noted, their assumption will be that the risk of using, or passing under, a bridge is negligible, if not zero.

1.2. Failure

Failure in any sector is almost inevitable. Across the range of engineering disciplines, most have the relative luxury of being able to produce, test and refine prototypes to ensure that the finished product is as risk free as possible. That process is a microcosm of that which civil and structural engineers have to follow as they develop concepts and ideas for various structural forms and materials. The fundamental difference is that the first can be conducted in a controlled environment, away from the public gaze, whereas the second is in full view and open to both scrutiny and criticism.

A failure of a small mechanical or electrical component while under development in a laboratory will help to inform decisions taken to ensure that the finished product meets all expectations. While a failure of a bridge can also help to inform the wider bridge engineering community, this only works if causes are investigated and reported, and the knowledge gleaned is made widely available.

This loop of continuous learning, applicable to all aspects of engineering, is summed up perfectly in the strapline of Henry Petroski's book, *To Engineer is Human – The Role of Failure in Successful Design* (Petroski, 1992). Or, to put it even better, as he does in a chapter title: '*Falling down is part of growing up*.'

Moving away from engineering, the worlds of commerce and business also recognise that there is value in failure. The UK entrepreneur Deborah Meadon has suggested that failure is a critical aspect of delivering successful business models (Meadon, 2022). The exact same principles of learning lessons, and sharing experiences, from failures can be applied in every walk of life: that we must learn from our mistakes.

Failure in bridges, however, is at a different level in terms of consequence. Although a failed business venture may cause financial hardship or even personal ruin, it seldom claims a life. Bridge failures, especially catastrophic collapses, are, more often than not, fatal.

Perhaps the closest parallel to a bridge is the modern airliner. Both carry large numbers of people and freight; and both defy gravity. Both also need rigorous inspection regimes and maintenance schedules. There is a difference, however, which is the quantum step between the attention given to aircraft and that given to bridges. I suggest that this is in part due to public perceptions of risk which are reflected in the priority that respective professions (and owners and operators) give to safety. The aerospace sector recognises the roles that various parties play in contributing to safety and sets a very high bar to prevent failures (Tremaud, 2010). This is a standard which the collective bridge engineering profession would do well to emulate.

All civil and structural engineers engaged in the design, construction, management and maintenance of bridges should have a broad interest in the historical development of structural forms and materials of bridges. Although many of these may be the legacy from centuries past, they still remain today as vital elements of our transport infrastructure for which bridge managers must continue to be responsible. That interest, however, should also extend to how the profession has benefited from past failures (Collings, 2008). Specific organisations must also learn from failures (Wearne, 2008). Wearne considers examples of post-war failures in the broadest spectrum of engineering sectors, from the 1956 Uskmouth turbogenerator failure to the Hatfield train derailment in 2000.

A specific engineering sector in which the consequences of failure can lead to multiple fatalities is chemical engineering. The UK's Institution of Chemical Engineers marked its centenary in 2022 by producing an online 'lessons learned database' (IChemE, 2022) in which detailed summaries of events are publicly accessible so that, hopefully, they will not be repeated.

1.3. Design life expectancy

Before delving deeper into this topic, it is worth commenting on the anticipated, or 'design', life of a bridge. The current theoretical design life in the UK is 120 years. This is nothing more than an arbitrary number which by no means should suggest that a bridge reaching this age would have to be demolished before it collapsed. Many bridges, notably masonry arches, have lasted many times this figure and have required only minimal maintenance interventions during their working lives.

While the primary intent of this book is to focus on total, catastrophic failures, it must be remembered that there are some bridge elements which will never meet the same design life as the bridge as a whole. Examples here would include bearings and expansion joints which will probably require replacement on numerous occasions during a bridge's life. The working life of these elements is very hard to accurately predict, being determined by many other factors, from vehicle numbers and weights even to the weather conditions when they were installed. Failure of other, more structural, elements could be much more serious, however, and these may be early symptoms which should be treated with some concern as precursor events, which are discussed in detail below.

1.4. Context

My interest in bridge failures and collapses has developed as my bridge engineering career has progressed. Since 2010, it has been my privilege to have been the Technical Secretary of the Bridge Owners Forum, a role which has given me a front-row seat in our consideration of all bridge management matters, including reflections on collapses. My personal epiphany moment, however, was in 2007.

From 2005 to 2009, I had both the pleasure and responsibility of chairing the UK Bridges Board (UKBB). This was (and still is) a group of senior bridge engineers representing all bridge interests and sectors from each of the four countries in the UK, including devolved governments. The UKBB focused not only on high-level strategy and policy but also aimed to identify possible weaknesses in its collective approach to bridge management. In the same period, I also chaired the Bridges Group of the County Surveyors' Society (CSS, now the Association of Directors of Environment, Economy, Planning and Transportation (ADEPT)). This group represented all local authority bridge owners (of which there were about 200) throughout the UK. This group's interests were more practical, and it was an ideal forum for knowledge sharing and peer support.

Almost exactly halfway through my tenures of these positions, on Thursday 2nd August 2007, the BBC Radio 4 *Today* programme's eight o'clock news announced that a bridge had collapsed in Minneapolis in the USA, during the evening rush hour of the previous day. I remember expressing some immediate concern at this news but, as the morning wore on, became aware of the emerging story: not just any bridge but an interstate highway bridge, over the Mississippi River. This was the I-35W, built only 40 years previously (Figure 1.1). One hundred and eleven vehicles had been thrown into the river, resulting in 13 fatalities and another 145 injuries. More details of the I-35W collapse are given as a case study in Chapter 6.

At home that evening, I had a phone call from a *Sunday Times* journalist who wanted something to quote along the lines of: 'Well, this is America. It couldn't happen here in the UK, could it?' My view then has little changed from what it is now: well actually, yes it could.

1.5. Precursor events

Before returning the focus to bridge failures, it is helpful to consider the theory of precursor events. These are akin to warning signs for motorists when there are possible hazards on the road ahead, or warning lights on the dashboard to show that there could be potential problems with their vehicle; they raise awareness that things may not be as straightforward, nor risk free, as they might appear.

Figure 1.1 I-35W collapse (courtesy of Mike Wills, 2007)

The initial notion of precursor events stems from the US aerospace sector and in particular the Aviation Safety Reporting System (ASRS, 2023). The model was later adopted and developed in the UK by CROSS-UK (Collaborative Reporting for Safer Structures) (Soane, 2021). The general concept is shown in Figure 1.2. This generic 'pyramid of risk' can also be transformed more specifically to consider bridge deterioration, as in Figure 1.3. In this case, however, the numbers of bridges at each level have only been illustratively quantified; there are innumerably more bridges in very good shape than those whose condition might be poor enough to fail, risking life and limb. This concept is further developed in Section 1.6 with a spectrum of deterioration as shown in Figure 1.4.

The thesis is that before any failure, there would have been other similar occurrences which should have given some level of advanced warning that things were not as they should be. Such occurrences may well not even have been on the bridge in question but possibly on another bridge of similar form, elsewhere in the country or even abroad. This gives added emphasis to the need for knowledge sharing. An example of the latter point is given in Chapter 5 in the case of the 1985 collapse of the Ynys-y-gwâs bridge.

The issue for bridge managers is, firstly, to recognise precursor events and, secondly, to be prepared to act. The former requires not only the appropriate degree of competence but also sufficient experience to understand when there is a potential problem. If those qualities are lacking, such as might well be the case with a newly appointed, inexperienced bridge manager, it is essential to know one's limitations and seek advice from one's peers.

Some recent examples of missed precursor events are among those case studies included in Chapter 6. Another relates to the collapse of the partly erected FIU footbridge in Miami, USA, in 2018. Here, precursor events were plainly visible for all to see; and yet were ignored. This collapse was the subject of a rigorous investigation by the US National Transportation Safety Board

Figure 1.2 The pyramid of risk (concept courtesy of ASRS and CROSS-UK)

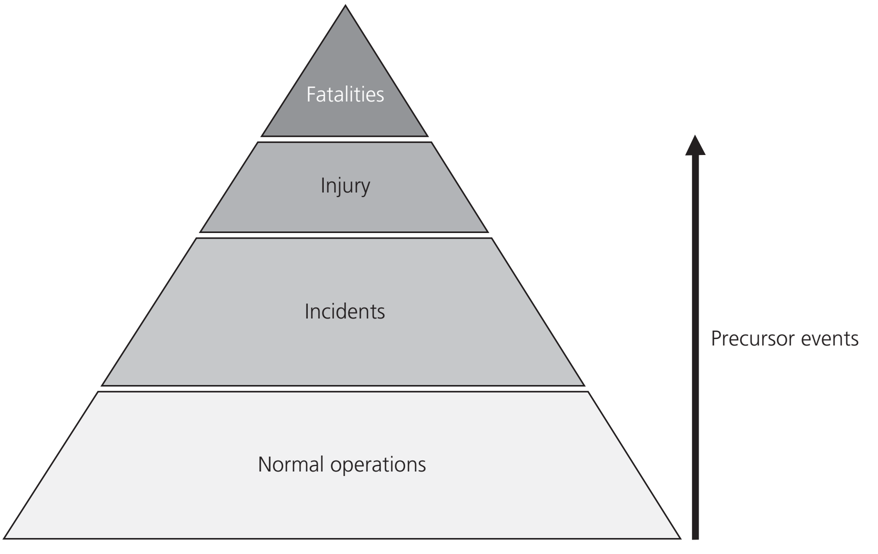
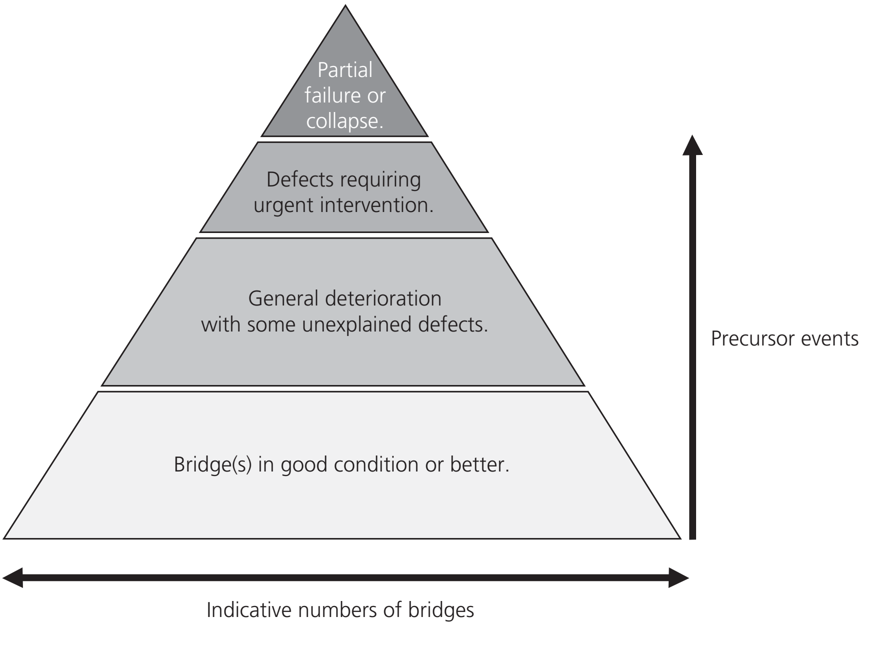


Figure 1.3 The pyramid of risk for bridges (concept courtesy of ASRS and CROSS-UK; Author's own)



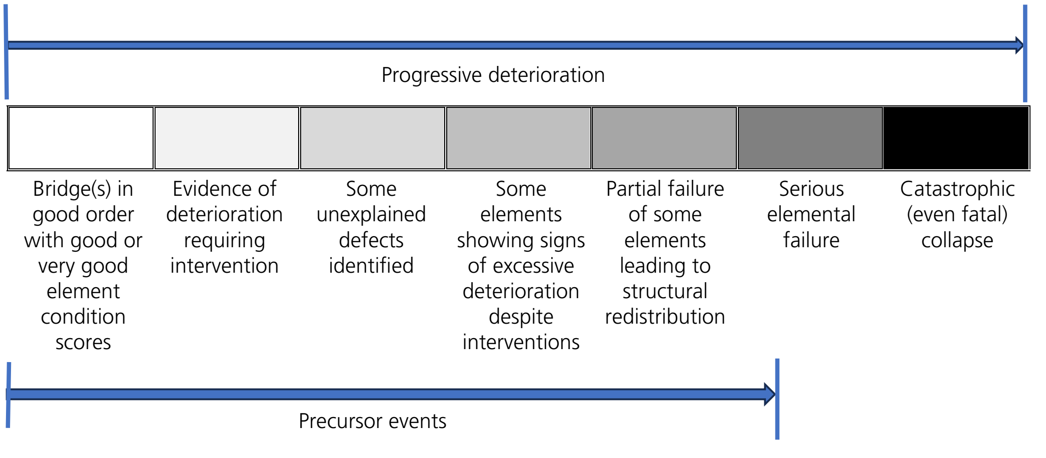
(NTSB, 2021). An excellent summary is also available from CROSS-UK (CROSS, 2020). This collapse is also covered in Chapter 8 with regard to risk, and more details of the roles of both of these investigatory organisations are given in Chapter 4.

Being prepared to act on a precursor event requires a conviction that something needs to be done and a commitment to make sure it happens. Being a bridge manager is not an easy role. As per the view of the late eminent bridge engineer, Dr Bill Harvey, there should be 'a constant low level of anxiety' for all who are charged with managing bridges (Harvey, 2021).

1.6. Perfection to disaster

Even defining what constitutes a bridge failure is not easy. At one end of a long spectrum (as shown in Figure 1.4) would be a total collapse, such as that of the I-35W bridge in 2007, leading to multiple fatalities and injuries. At the other end would be a bridge, or a bridge stock, with no apparent indication of problems. And even if a bridge manager was to find themselves in this utopian situation, there should still be no room for complacency. Indeed, in order to keep the bridge or a stock in this theoretically near-perfect condition would have required significant investment through an adequate and protected budget, a competent workforce, and a bridge inspection and management regime designed to literally maintain the status quo; to keep it in a steady state.

Figure 1.4 Bridge deterioration spectrum (Author's own)



From this unlikely position of perfection, moving to the right a notch, would bring us to the real world where, inevitably, there would be some evidence of deterioration, if only through the law of entropy. That would be at a level of deterioration, however, of which the bridge manager should be fully aware; one in which their bridge management practices, built on sound, competent inspections, provide an accurate picture of the state of their bridge or stock. This would be the real world at its best, with sufficient resources available to undertake the necessary interventions to return to the steady state.

Even the next step in the spectrum also remains in the real world, where defects have been identified and accurately recorded which will cause the bridge manager some concern; to scratch their head or rub their chin. Defects which are either unexpected or not easily explained. But at least they have been identified and provide the opportunity to think hard and long about any cause-and-effect relationship.

Another step might be a case in which a planned or reactive maintenance intervention proves not to have been successful – for example, a repaired crack which reopens or continuing settlements behind an abutment. This might be a flag to those precursor events as discussed in Section 1.5.

Moving on from there would come the point of a partial failure, which could be described in risk management terms as a near miss or a close call. Any such event, however, should be a wake-up call and it is at this point that knowledge sharing should become not just desirable but essential. No bridge manager should ever work in isolation. Support networks should be in place with the appropriate level of mutual understanding that ensures that problems can be shared and advice from peers be made readily available.

The consequence of partial failures of elements depends on the structural form and levels of redundancy. It is not impossible, that even a partial failure of a critical element will trigger a total collapse, but, more probably, there will be some redistribution of load effects into adjacent members. Even the latter, however, should be seen only as a temporary state of affairs. This should lead to immediate and urgent action, such as a road closure over the bridge and taking measures to prevent access below.

Looking after any ageing infrastructure requires investment in terms of both money and people. And that is just to keep things at a steady state. Unless the right level of funding is allocated and protected for bridge maintenance, the movement to the right on the spectrum will continue. Politicians must be encouraged to reject the photo-opportunistic, ribbon-cutting, perceived-vote-winning ceremonies for new bridges, and invest in what might be considered as the less-than-sexy maintenance of the existing: the ones that potentially will kill people.

1.7. Economic consequences

Although human life has to be the most valuable commodity, another factor that must be taken into account when considering the consequences of a bridge collapse is economics, in terms of the effects to both local and national economies. Almost by definition, the connections that bridges make between communities or, especially in more rural areas, *to* communities is immeasurable. Sever such links and there will be multiple problems, not only through an immediate economic hit but also in the subsequent impacts on deeper social issues such as accessibility, poverty and deprivation.

Highway bridges, of course, do not just carry vehicles. More so than ever before they carry utility company apparatus, from the basics, such as water, gas and electricity, through to the non-life-threatening, but ever more essential, facilities such as broadband fibre.

Whether it is connections for people or for utilities, there is seldom a quick fix – for example, when the county of Cumbria in the UK was hit with a devastating rainfall event in November 2009, the port of Workington was effectively split in two when five bridges over the river Derwent either completely collapsed or suffered damage to the extent that they had to be subject to lengthy closures, pending inspections and significant maintenance interventions. One, Northside Bridge, claimed the life of a policeman who was bravely preventing traffic from using the bridge. As well as the human tragedy, the loss of services and access had a significant and long-lasting economic impact on the community (Smyth, 2011). This flooding event, and its consequences on the Cumbria bridges, also led to evidence being given to the UK Government's Transport Select Committee (Transport Committee, House of Commons, 2010). A change of government in 2010, however, meant that no formal report was ever made public. As the primary cause of these failures was scour (Section 10.3.1), another consequence was a revised standard for scour inspections, based on a risk approach (National Highways, 2012).

1.8. Investigations and reporting

Very sadly, bridge collapses continue to kill people. Case studies in later chapters delve into a level of detail which can only be described because there had been a rigorous investigation and, usually, an official report having been made publicly available. Such forensic scrutinies into the causes of a collapse, however, are the exception rather than the norm. There is no international standard for reporting and the quality of publicly available information ranges from excellent to zero, depending on the transport operator and/or the country in question. This topic is covered in detail in Chapter 4.

1.9. Ethical responsibilities

Aside from the physics, and the engineering analyses, of failures, there is also the question of the behaviours of those whose fingerprints might be found on a failure. As noted above, the burden of responsibility can be significant and decisions on when or whether to intervene in a bridge's life can literally be a matter of life or death. The point here is to appreciate and accept those responsibilities and to act with integrity and honesty throughout the decision-making processes. The most important characteristic of all, however, and one worth repeating, is to know one's limitations; to know when to ask for help, when to seek advice or a second opinion, and when (and how) to escalate an issue to senior managers or politicians.

Chapter 9 discusses these ethical issues not only with respect to bridges but also by looking at other engineering sectors in which, unfortunately, there are many recent examples of unethical behaviours leading to disaster.

1.10. Conclusion

This chapter has simply been a reasonably brief overview across the breadth of the various issues associated with bridge collapses. Other chapters drill deeper into each of the subjects that have been touched upon above. The fundamental point, however, is the need for a thorough, professional approach in all matters pertaining to bridge maintenance and bridge management.

As for the form of the book, it is split into two parts. Part 1 looks backwards at failures and collapses that have occurred over the last two millennia. This is not, however, simply a list of failures – case studies have been chosen not only to illustrate the tragic consequences but also to show where lessons have been learnt and that, as a result, both our collective engineering knowledge and public safety have been greatly improved. Part 2 is forward looking. Do we fully understand the condition of our bridges, including hidden and vulnerable details, and do we fully appreciate risk? Is our collective moral and ethical compass emphasising the burden of responsibility that bridge managers share in their day-to-day work? And are we fully aware of what the future holds, both with the added pressures of climate change and the benefits that emerging technologies might be able to provide to make our professional lives easier?