1 Introduction

1.1 Retrospect

My career in construction began in 1946. This was shortly after the end of World War II and I was unable to find a place to study in a faculty for civil engineering because the German universities were overcrowded and older applicants, many of them returning from the long war years, were rightly given preference over us school-leavers.

I therefore started an 18-month building apprenticeship with the aim of becoming a skilled construction worker. At that time I was living in Bremen on the right bank of the Weser and my work took me to a building site in Neustadt on the left bank. It was there, on 18 March 1947, that I witnessed the Bremen bridge catastrophe [1]; surging ice masses swept in by floodwater, together with unmanned boats and barges torn from their moorings, destroyed all the bridges in the town in the space of only a few hours. In the morning I had crossed over a road bridge from the right to the left bank and in the late afternoon I returned to the right bank of the city on one of the last trains over one of the last bridges still standing. This bridge too had been swept away by late evening. The lesson I learned from this disaster was that even with consideration of the fact that immediately after the war the conditions on the river Weser in the city of Bremen were provisional and unusual in many ways, in the end human beings can often only do little in the face of the forces of nature and sometimes nothing at all.

Fortunately, no one was killed in this, my first experience of a collapse disaster. The same is true for the second failure event, which I clearly remember from my practical work on the building site. During concreting of a coal bunker for an industrial power plant, a column-mounted, open-topped cubic box with a side length of approximately 12 m, the inner formwork gave way just above ground level shortly before all the walls had been filled. Most of the concrete spilled out onto the floor of the bunker, accompanied by a dreadful noise I clearly remember even to this day, over 60 years later, caused by the friction of the gravel against the wooden edges of the hole in the formwork. Once the experts had ascertained that the floor scaffolding would not collapse under the huge weight it had not been designed to bear, we worked for hours using buckets on ropes to take the concrete up and out of the bunker. What did I learn from this? The pressure on formwork can be enormous; 24 to 26 times height in meters in kN/m^2, and that was something I never forgot later when working on a new standard for scaffolding. And also that concrete, which is no longer needed, can never be allowed to set; the fire brigade can be very helpful here.

We heard little about building accidents or the failure of load-bearing structures during our studies at the University of Darmstadt. Certainly our Professor for Steel Construction referred to the collapse of the civic hall in Görlitz in 1908 [2] to teach us what we should consider when using gusset plates to join chord members. And some years later, this lecturer Kurt Klöppel, told us as his assistants about the terrible accident during the building of the Frankenthal Rhine bridge in 1940 [3], where 42 were killed, and about his investigation into the cause of the failure. From this I learned some basic rules: firstly, that bad luck (see Section 3.7) can always be in play and that engineers must therefore be thorough and imaginative when thinking through the possible failure scenarios. Secondly, that short and simple rules such as long members being more liable to buckle than short members should only be used with the greatest of care because, like all rules, they only apply in certain circumstances. In Frankenthal, it was a short pin-ended wall in a truss system susceptible to buckling, which became so dangerous on account of the great deflection forces.

K. Klöppel made frequent reference to the two German failure occurrences involving bridges built with the new structural steel St 52 in the mid nineteen-thirties – the railway

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bridge over Hardenberg Street in Berlin and the motorway bridge at Rüdersdorf [4] near Berlin (Section 4.8). This taught me that in civil engineering, as in medicine, an empirical procedure of observation, classification, and analysis can be helpful in averting danger in addition to the strictly scientific analysis of all the contexts. In connection with these two bridge failures, Klöppel was the guiding spirit of the "Preliminary Recommendations for the Selection of Steel Quality Groups for Welded Steel Construction" in 1960, which led in 1973 to Directive 009 of the German Committee for Steel Construction.

In 1954 the motorway bridge over the Lauterbach Valley near Kaiserslautern collapsed during reconstruction, fortunately without causing any deaths or injuries. Kurt Klöppel was commissioned with the inquiry into the cause of the accident and I was among the group of assistants working on the case. The accident and its causes are described in Section 3.3 of this book and it suffices again here to say what I learned from this failure: intermediate states during construction generally lead to extreme stressing of the component parts and must therefore be recognized and carefully investigated.

The collapse of falsework for the reconstruction of part of the motorway bridge over the Lahn Valley near Limburg [5] in 1961 killed 3 building workers and injured 11. I was on the scene of the accident shortly afterwards as a young consulting engineer working out of Wiesbaden. I remember feeling the great responsibility, which is part of our profession, and was acutely conscious of the risk that we can never fully avert.

10 years later I hurried to Koblenz, where a road bridge over the Rhine had collapsed during erection [6]. This incident, together with several other, apparently similar occurrences (Section 3.4), unavoidably resulted in an overreaction in international professional circles, in which I too participated, to prevent any recurrence of this type of failure during the construction of steel box girders. I also took part in the subsequent research, which led to a safe method for the assessment of the bearing capacity of stiffened steel plates as later implemented in building regulations.

I was back in Koblenz just one year later, this time appointed by the public prosecutor to investigate with my two assistants the cause for the collapse of the falsework for one of the last construction stages of a multi-span bridge (Section 11.4.1). 6 had been killed and 13 injured. In the course of this investigation, my belief was confirmed that the work of an expert witness must be determined only by the investigation into the cause of the incident and that even the most insistent demands for initial comments from representatives of the media must be refused.

During my 30 years of experience in the construction of guyed masts, reports of damage during construction and the large number of mast collapses all over the world including fatal accidents to mast erectors in the course of their work have impressed upon me the risk involved in the design, erection and operation of structures of this kind. It is therefore no surprise to me that many mast collapses occur during construction or reconstruction and I ask myself: were all the people involved adequately informed of the inherent danger of their actions, and has enough been done to prevent them from behaving like the "Sorcerer's Apprentice" and bringing calamity upon themselves and others?

My own experience reflects what everyone "on site" knows: building work is often linked with failure; this has always been the case and always will be. Yet if we learn from the circumstances and mistakes leading up to disasters in the past, we may possibly help to reduce the number of failure occurrences, collapses and catastrophes in the future.

1.2 Aim

In the days before engineering science made it possible to predict the behavior of load-bearing structures, failures were the main source of education and progress for builders. In the same way today, load-bearing structures must prove themselves in practice. Machine and particularly car makers can run a pilot series to remedy defects before going into production, but the one-off nature and size of building structures make it impossible to test their load-bearing capacity and remove defects before construction.

When analyzing the causes of structural failures today, I find that there is hardly any case, which could have been prevented by more detailed calculation. Colleagues such as D. W. Smith [7] or O. M. Hahn [8] have looked into this question and have come to the same conclusion. The basic cause of most catastrophes was either that possibilities of failure were never even considered, conditions were not thoroughly investigated or that in some way rashness or even foolishness was predominant during design or construction. Also on some occasions, successful structures have been the cause of failure in later structures when seemingly unimportant changes, such as in size or slenderness, turned secondary factors into major influences [9].

It is also doubtful whether the safety theory based on a probability approach, which is now the basis for all new standards internationally, is likely to reduce the incidence of failure and collapse of structures. This is because the causes are not statistically distributed, but are rather gross errors that do not fit into any probability calculation. Such concepts are perhaps better suited for appraising the serviceability of our structures.

As engineers continuously produce technical innovations with increasingly challenging load-bearing structures such as bridges with wider spans and of lighter design, cranes of higher lifting capacity and taller skyscrapers and towers, it can happen that due to the limitations of their standard of knowledge, they fail to identify hitherto unknown phenomena and dangers. They are often forced to extrapolate and to accept the risk this entails [10]. Here the progress made in the science of structural engineering has not brought about any radical changes.

H. P. Ekardt [11] spoke of the experimental practice of engineers and comments at one point: “Construction is in a state of continuous development, progressing through emergency situations and constantly breaking new ground in actual projects, creating something new, and in this respect is removed from state or legal control – the area to be controlled is in itself insufficiently objectified and defined for the requirements of law. What is needed is professional self-control based on knowledge, experience, balanced judgment and responsibility. Control and self-control are the two poles between which the practice of designing innovative load-bearing structures moves, particularly when the area of technology involved is in a state of rapid development. The effects of this professional self control are strengthened when setbacks are described, which manifest themselves in the failure of load-bearing structures, their causes discovered if possible and lessons drawn from them.” The foreword began with a quotation from George Frost [12] and in this sense these descriptions are intended to contribute to the science of engineering. This is the concept of my book.

The documentation of failures of load-bearing structures contained in this book does not aim to lecture the people involved in their design or construction after the event – as long as we exclude failures resulting from lack of responsibility. We should bear in mind that this is always easy after the failure has occurred. For this reason, the incidents are only described without naming the parties concerned, except in historic cases. I consider this to be appropriate in order to be fair to the colleagues affected while at the same time making use of the lessons their cases provide.

1.3 Structure

1.3.1 General information about the tables

The tables contain all the occurrences of failure, for which I was able to obtain adequate information. Of course, the question arises whether this form of documentation is useful. I have decided to use tables for the following reasons:

- Reports on failure events are scattered throughout scientific literature. I felt that a compilation of the cases known to date was called for.
- When statements are made about the frequency of failure types and causes, although they cannot fulfill statistical requirements because the total number of incidents is unknown, the sheer number of cases supports their validity. In particular, the availability of descriptions of cases in the tables means that the reader is not obliged to blindly follow my assessments. This is unfortunately not always true of summarizing works such as [7, 23].

The failure occurrences contained in the tables include details of the structure, the year of the failure and the number of people killed or injured. The reason for the failure is briefly noted and the main dimensions of the structure are given in rounded meters, when known, together with at least one source.

1.3.2 Structures included

Despite all the efforts made to ensure that information is comprehensive, a lot of chance is involved in the compilation of failure cases. The source references in the tables show how large the reservoir of information is. Nonetheless, the causes of and course of events leading up to certain cases of failure remain unknown to me although, due to their severe consequences or because of the important lessons to be learned from them, they should have been included. There are many different reasons for this; the degree of candidness in reports on failure cases varies greatly from country to country and the legal difficulties involved in objective reporting have increased over the years.

The data is not representative enough for statistical statements - and it is particularly important not to draw conclusions related to specific countries, as is unfortunately often done. Nevertheless, I have cautiously attempted to identify certain trends in the causes of accidents.

1.3.3 Causes considered

All causes of damage have been considered with the exception of acts of war, chemical action and natural catastrophes such as volcanic eruptions and landslides. Landslide hazard to bridges can often be avoided by a slight adjustment to the positioning of the bridge.

1.3.4 Sections of the book

I have arranged the book in the sections listed in Table 2, although different arrangements present themselves. The failures listed in Tables 3 to 11 are in chronological order.

1.3.5 Sources used

The primary sources for the failure cases included in this book are the publications on failures of load-bearing structures listed in Section 1.4. I have attempted to use the original reports named in these for my research and, as far as possible, have not depended on interpretations contained in later works. I have not always succeeded in this due to the vast number of cases: 440 + 96 = 536 are listed in the tables.

Further sources include expert reports made available to me by colleagues, my own expert reports, building authority records and also newspaper articles.

1.3.6 Abbreviations

The source column in the tables generally names at least one source per case, when possible the original source or a source relatively easily available to the reader which I have also used whenever possible. The source information in the tables is brief because the space provided does not allow full documentation of title and author. Table 1 lists the abbreviations selected for frequently used sources in alphabetical order.

Table 1 Abbreviations for sources used in Tables 3 to 11

Abbr.	Source, mainly journals	Details given
B + E	Journal "Beton + Eisen" (Concrete and Iron)	year, page
BI	Journal "Bauingenieur" (Civil Engineer)	year, page
BRF74	Manuscript for lecture at Conference of German Bridge Consultants Düsseldorf 1974	
BRF76	as above, Passau 1976	
BuSt	Journal "Beton- und Stahlbeton" (Concrete and Reinforced Concrete)	year, page
BT	Journal "Bautechnik" (Structural Engineering)	year, page
BMV82	Schäden an Brücken und anderen Ingenieurbauwerken-Dokumentation 1982 [5] (Damage to bridges and other civil engineering structures)	page
BMV94	as above, Documentation 1994 [13]	page
CivEng	Journal "Civil Engineering"	year, page
EB	Journal "Eisenbau" (Iron Construction)	year, page
El	Elskes, E.: Rupture des ponts métalliques [14] (Failure of metal bridges)	page
ENR	Journal "Engineering News Record"	year, date of issue, page
IABSE	IABSE Colloquium Copenhagen 1983, Introductory Volume [15]	IABSE, p.
IRB	Documentation of Fraunhofer Information	Document No.
	Centre IRB, Stuttgart	
Pott	Pottgießer, H.: "Eisenbahnbrücken" [85] (Railway Bridges)	page
Sm	Smith, D. W.: Bridge failures [7]	page
SB	Journal "Stahlbau" (Steel Construction)	year, page
SBZ	Schweizer Bauzeitung (Swiss Journal of Building)	year, page
St	Stamm, E.: Brückeneinstürze und ihre Lehren [16] (Bridge collapses and their lessons)	page
W	Walzel, A.: Über Brückeneinstürze [17] (About bridge collapses)	page

1.3.7 Overview of failure cases

With reference to the tables, I have first made general observations as to the causes of failure for most of the structure types, including the attempt to allocate the failure occurrences to a specific cause category. This method frequently comes up against difficulties as described by Walzel as early as 1909 [17].

The question *what was the cause* is answered in various ways: where possible I have decided to give priority to reasons inherent in the actions of the participants over the technical causes resulting from these actions, since more can often be learned from the former. If, for example, a lack of information on the construction site led to a course of action that caused a failure, as a result of, say, overload, I have identified lack of information, i. e. a rash or irresponsible action as the primary cause of the failure and not the overload.

- Often several causes are responsible for the failure: nothing would have happened if only one or the other defect had been there.
- Allocation to a cause can also frequently be imprecise due to gaps in the data available. In these cases, the findings are of necessity subjective and have nothing to do with statistical science.

Following this, the cause or causes of the failure and the lessons to be learned from them are described in more detail for certain selected cases. The summarizing comments on certain groups of accidents allow or require more pertinent observations and conclusions. New insights in connection with the development of structure types and the experience gained can lead to measures being taken to prevent repetition of mistakes, such as the revision or supplementation of building regulations.

The lessons learned from the failure occurrences are described in Sections 12 and 13.

1.4 Earlier publications on the failure of load-bearing structures

As far as I know, the oldest summarizing documentation of building accidents was by E. Elskes [14]. In 1894 the author described, unfortunately without a full source reference, 42 collapses of iron bridges between 1852 ands 1893 and listed them in a table according to the following classification:

- Failure of foundation,
- failure due to unusual effects e. g. impact,
- collapse during construction or dismantling,
- failure during load testing,
- insufficient load-bearing capacity without other recognizable causes.

To this day, the most famous of these collapses is that of the railway bridge over the Firth of Tay in Scotland in 1879. One notes that the calamitous collapse of the Mönchenstein bridge (later known as Münchenstein) over the river Birs near Basle, Switzerland in 1891 is not included in the table, although two collapses in 1893 are listed. 16 excellent drawings give the reader an impressive view of the accidents.

In 1909 A. Walzel also reported on bridge collapses [17]. He thoroughly described and analyzed 16 cases of bridge failure from 1868 to 1908, amongst others as in [14] the Firth of Tay catastrophe (1879), Mönchenstein (1891) and the first of the two collapses during construction of the bridge over the St. Lawrence River near Quebec (1907). He wrote: “Now, at the end of my deliberations, I believe I can truthfully claim that each of these accidents is very instructive for the builder.” He cited the famous English engineer Isambard Kingdom Brunel (1806 - 1859) (see [18]), who built numerous wooden railway bridges and in 1829 the 214 m long Clifton Suspension Bridge over the Avon Gorge near Bristol. After the collapse of one of his bridges, Brunel had the audacity to congratulate his employer on this occurrence on the grounds that he had been planning to erect a further dozen bridges of this type but would now have to revise his plans (see also Section 4.4).

In 1921 F. Emperger published a section on building accidents in a manual for building with reinforced concrete [19]. He described the failure of reinforced concrete structures in the early days of this new method of construction and divided them into accidents resulting from natural disasters, from irresponsibility and from defects in design and construction. I quote from the introduction: “Accidents are conclusive proof that serious mistakes or acts of negligence have taken place during the erection of a structure. It is therefore necessary to investigate the causes of these phenomena in order to instigate effective accident prevention. The list of such events, ordered by their causes, contained in this chapter primarily serves to achieve more perfect safety of our structures. … The accidents provide a guideline through these reports, because their history is closely linked with the progress of technology in all its areas as it strives to remove existing defects and to expose ignorance and prejudice.” He emphasized the value of statistical records of construction accidents and commented: “They (statistics) will make a major contribution to scientific understanding.”

E. Stamm’s book [16] appeared in 1952 and is often regarded as one of the classic works on collapses of iron and steel bridges; failures of wooden and stone bridges are not dealt with. Stamm adopted the 42 accidents registered up to 1893 contained in Elske’s book [14] together with the drawings already mentioned and added some 100 failure occurrences from the years 1891 to 1950, illustrated in many cases with photographs. Some incidents are dealt with in greater detail, such as the two partial collapses of the bridge over the St. Lawrence near Quebec (1907 and 1916), the collapses of the Thur bridge near Gütikhausen in Switzerland (1913), the Birs bridge near Mönchenstein (1891), the Tacoma Narrows suspension bridge in the USA (1940), the damage to the bridge over Hardenberg Street in Berlin due to brittle fracture and the Rüdersdorf motorway bridge near Berlin in Germany (1938) and also several partially collapsed bridges over the Albert Canal in Belgium (1938 to 1940). Stamm largely limited his description of other collapses to categorizing them according to failure causes such as mistakes during erection, overload, external influences, aerodynamic instability and brittle fracture. Sources are provided for almost all the events covered, but there are unfortunately no clear summaries in table form.

The number of publications in English professional journals dealing with the incidence of damage in bridge building increased from 1976 onwards. One of the most important in my opinion is the work of D. W. Smith *Bridge failures* [7], primarily because it started an important discussion [20] in which many influential bridge engineers from various countries participated. The work is centered around three tables detailing 143 bridge failures with the date of the collapse (between 1847 and 1975) the age of the bridge at the time of collapse, the cause and the number of dead and injured. One striking fact is the large number of failure occurrences caused by flood catastrophes (almost half of the 143) and the rapidly increasing amount of damage by ship collisions, the latter due to the simultaneous increase in the number of ships and multi-span bridges over navigable waterways. Smith particularly pointed out that only one of the collapses he investigated was the result of an inaccurate structural analysis, he emphatically and correctly warned of the danger inherent in complicated and sometimes ambiguous codes, and for this he found the support of many colleagues. The discussion is well worth reading even now, over thirty years later, because it draws the bridge-builder’s attention to many problems that are still relevant today. The German author U. Peil examined Smith’s work and the subsequent discussion in [21].

P. G. Sibyl und A. C. Walker published their book *Structural accidents and their causes* [22] in 1977 in which they reported on the history of the four catastrophes of large steel bridges: Dee (Section 4.4), Tay (Section 4.5), Quebec (Section 3.2) und Tacoma (Section 4.3)

Bridges. They all failed either during construction or shortly after being put into service. On the basis of the documentation, the authors concluded that the accidents had certain causes in common and that their stories contain lessons useful for today's practice. They also emphasized that the collection of statistical data and the classification of accidents provides an important service to the engineering profession.

The publication *Analysis of events in recent structural failures* by F. C. Hadipriono [23] in 1985 concentrated on a classification into the causes: mistakes in design, detailing and erection, flaws in maintenance and materials and natural disasters. While not evaluating individual cases, Hadipriono compiled a total of 147 failure occurrences divided into those concerning bridges, low-level, multi-storey and wide-spanned buildings (nine of the latter collapsed between 1978 and 1980 worldwide) and industrial facilities. His commentaries contain three conclusions, which are seldom mentioned elsewhere and deserve special attention: these are the risks arising from changes to or even abandonment of the design concept during design and construction and from staff changes in those accountable for the project. In both cases, information important to the safety of the project can go astray. His third conclusion concerns the risk inherent in modern construction management with many highly qualified specialists working alongside each other. This has often led to a break in the chain of information between the participants; coordination is therefore the central task – or should be. The aim of Hadipriono's study is that the evaluation will hopefully help the engineering and construction professions, which are affected by technical problems, and serve as a guide for better practice in the design and construction of similar structures in the future.

I mention the following examples to demonstrate the sheer scope of publications in the last decades:

In 1982 Lord Penney [24] compared not only the dangers involved with various technologies such as nuclear power engineering, mining, road traffic and civil engineering, but also the dangers to which humans are exposed over and above these such as sickness and smoking.

G. Dallaire and G. Robinson (1983) considered the potential danger when details of steel structures, especially connections and web joints, are machined by unqualified staff. They quoted Mies van der Rohe's *God is in the details* and commented that this observation, actually directed at architects, holds just as true for engineers. Having learned from bad experience, they demanded licensed detailers, warned against unwise sub-contracting of these jobs by the designers to other companies (they say fabricators) and emphasized that responsible inspection of construction details is at least as important as structural analysis. They hoped that the problem would be at least partially solved in time by very good and sophisticated software [25].

P. Oehme of Dresden University presented his thesis *Analysis of damage to steel load-bearing structures from the point of view of engineering science and in consideration of legal aspects* [26] in 1987. His observations were based on 564 failure occurrences (448 of which were in the former German Democratic Republic) in the years from 1945 to 1984, mainly documented in the files of various institutions in the GDR. 40 % of the incidents were in building construction, 28 % in bridge construction and the rest in mining facilities, cranes, masts, towers and other load-bearing structures. His work contains tables with details such as the age of the structure at the time of failure, the extent of damage and various notes on the causes of failure. Cases of extreme damage, i. e. those with a value of over 1 000 000 German Marks are given for 10 % of the failure occurrences in the GDR and 41 % in other countries; this difference is certainly due to discrepancies in the information available in the former GDR compared with other countries.

In 1990 J. Scheidler [27] described 14 serious failures during the building of large bridges of prestressed concrete, steel and composite steel-concrete construction. Except for the two early disasters during building of the Comelius Bridge over the Isar River in Munich in 1903

(Section 11.6) and the motorway bridge over the Rhine near Frankenthal in 1940 (Section 3.7), the incidents are dated from 1950 to 1990 and occurred in Germany, Switzerland and Austria.

W. Plagemann responded to [68] in 1994 by asking the uncomfortable question *Successful engineering – carte blanche for future structures?* [9]. Using the Dee Bridge disaster as an example, (Section 4.4) he described the danger in enlarging or slenderizing tried and tested structures when the "protective cover" of experience is overstepped and hitherto insignificant influences become predominant. My thoughts went in the same direction and are summarized in *Extrapolation – necessity and risk for civil engineers* [10] from 1994.

Several books on damage and accidents during construction have been written over the last 40 years. The following is a brief account of some of their aims and contents.

In *Cases of damage to prestressed concrete* [28] (1972) T. Monnier concentrated on buildings and bridges of prestressed concrete construction and commented in his summary that failure occurrences were mainly due to deficits in detailing and erection.

R. Rybicki's *Damage and defects in building structures – assessment, safety, repair* [29] (1972) aimed to provide a systematic guideline for the assessment, securing and repair of damaged or defective load-bearing structures in building and engineering account. He is primarily concerned with commonly occurring defects, their avoidance and rectification and juxtaposes examples with the principles which would have avoided them.

J. Augustyn and E. Śledziewski followed a similar procedure in 1976. In *Damage to steel structures – causes, effects, prevention* [30] they combined a description of basic principles for the design and construction of steel structures with a detailed account of 68 mostly serious failure occurrences in building, plant, crane, silo and bridge construction as examples of the consequences of their violation. Most of the incidents described occurred in countries east of the former Iron Curtain and were previously virtually unknown "in the west".

In 1982 R. Ruhrberg and H. Schumann were commissioned by the Minister of Transport of the Federal Republic of Germany to examine damage to bridges and other engineering structures [5]. Their documentation provides schematic accounts of 61 cases of structural damage, 14 accidents during construction and 9 damage incidents, all occurring in the years from 1959 to 1981. The cases of structural damage contain structural data, damage description, cause and remedy and the deductions drawn. Drawings and sketches are used effectively. The cases of accident and damage are described in some detail. The same applies to the following documentation appearing in 1994 [13] dealing with 49 further cases of structural damage, 16 further accidents and 12 further damage incidents.

Design and Construction Failures - Lessons from Forensic Investigations [31] by D. Kaminetzky was published in 1991 and is a systematically arranged review of possible defects in concrete, steel and masonry structures including foundations citing examples primarily from the area of building construction, in most cases with instructive sketches and photographs. His sarcastic quotation from J. Feld "The best way to generate a failure on your job is to disregard the lessons to be learned from someone else's failures" makes his intention clear: to avoid repetition of mistakes by using the lessons he draws from the accidents for each specific area of construction.

A completely different aspect of engineering is described in F. S. Ferguson's *Engineering and the Mind's Eye* [12]. The author shows how modern science has caused the engineer to lose the ability to see in his mind's eye and that this loss to the art of engineering can be the cause not only of simple construction errors, but also be responsible for catastrophes. Some examples from the field of civil engineering are the collapse of structures such as the bridge over the St. Lawrence near Quebec in 1907, the Tacoma Narrows suspension bridge in 1940 and the Coliseum in Hardford in 1978. His deliberations have in part led to new assessments of these well-known disasters.

In 1997 J. Feld and K. L. Carper presented the 2nd edition of *Construction Failure,* first published under the authorship of J. Feld in 1968 [32]. The revision extended and updated the first edition. Bridge failures constitute only a relatively small part of the book but it nevertheless covers 9 collapses of bridges in service and a few during construction. They particularly mention the shocking number of iron bridge failures towards the end of the 19th century. In 1895 the *Railway Gazette* had published a discouraging survey on railway bridge collapses listing 502 incidents during the years from 1878 to 1895 and pointing out that the first 251 cases had occurred in the first ten years and the second 251 in only eight years. There had been 162 accidents between 1888 and 1891. These reports were republished several times and avidly discussed. They must have had a great influence on the bridge engineers and builders of the time.

In 1998 M. Herzog in *Damage in Steel Construction and its Causes* [33] largely repeated facts already known. The causes of damage are occasionally given in a simplified form, reduced to one cause only, and are in my opinion not always correct.

H. Duddeck's deliberations in *Learning from mistakes ... ? How knowledge is gained in technology* [34] (2001) are set in a larger framework. It becomes clear that learning from accidents, that is from doing things wrong, is only a part of learning-by-doing for engineers, although an important part, because often associated with the exceeding of limits.

A new edition of B. Åkesson's *Understanding Bridge Collapses* [35] was published in 2008. This deals with 20 examples of failure events (often repeatedly – as in the first edition) and he correctly points out that the causes of failure are relatively seldom to be found in calculation errors but are mostly false assumptions, material defects, poor supervision, disregard of fatigue, instability and aerodynamic weaknesses.

In 2004 I. Rust [134] presented a socio-scientific analysis of risk management in engineering practice and science including problems in bridge building. Her findings are based on an approach that integrates social and engineering science and are summarized in Section 4.1 in 29 clearly formulated modules.

From the above publications, it emerges that there have been repeated demands over the decades for failure occurrences in structures to be reported. This took place in Germany, for example in the case of reinforced concrete construction, where every failure until 1912 was reported to the engineering world in the journal *Beton und Eisen* (*Concrete and Steel*). A gazette published by the building authorities later took over this function (see also [29]). Unfortunately, in the course of time, its reports became increasingly incomplete to the point where nowadays, due to the availability of sources, particularly in the USA, there are more German-language publications about overseas failure occurrences than about those in our own country (I have already mentioned the exemplary publications [5 and 13] which are exceptions here). It would therefore be entirely wrong to conclude that the failure quota is higher abroad than in Germany.

It is a moot point whether one can speak of “the growing recognition that failures should be documented” as suggested in *The History of Famous Bridges* ([36], page 44). It is true that legal considerations often stand in the way, yet if the personal assessment of a recognized expert is documented and published as a subjective opinion, no objection should be raised. It follows that all of my own descriptions and assessments should be regarded as subjective and competent experts using professional argumentation are welcome to correct them.

1.5 Estimated numbers of bridges in Germany and USA

As mentioned in the foreword, some figures should be given to allow the numerous cases of bridge failure contained in this book to be related to the actual number of bridges in existence. Unfortunately , neither the German Federal Office of Statistics nor the Ministry of

Transport is in possession of a complete inventory, the latter only listing road bridges for which it is responsible and thus not including bridges in the responsibility of the German states or local councils. According to the figures available, 35 000 bridges were listed under or over motorways and main roads in 2008. The number of railway bridges in Germany is presently estimated at 29 000 to 30 000.

According to a survey appearing on the Internet (2007 Bridge Inventory) dated September 2007, there are approx. 600 000 bridges in the USA, of which approx. 290 000 are interstate and state bridges and approx. 310 000 city, country and township bridges. See also [137].