

# Development of Safety in Structural Standards

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**ABSTRACT:** Nowadays, the required safety of structures is achieved through computational verifications and qualitative requirements for the building materials and the construction processes. Both the computational verifications and the qualitative requirements are shaped by increasingly specific scientific investigations and by political framework conditions. The target values of the required safety are largely developed by models focused on individual limit states, although individual collapses have an impact on the standards. An examination of safety across the entire stock of structures has not yet been carried out. In this paper, the safety of the stock of structures is determined from the ratio of the median calculated failure probabilities of different calculations and the median observed collapse frequencies over all structures. The ratio shows the absolute safety, i.e., the sum of safety from computational verifications and qualitative requirements. This allows an assessment of the quality of research and standardization work.

## 1. INTRODUCTION

Structures must be designed, calculated, built, and maintained in such a way that their safety meets the requirements placed on them over their service life. The safety is defined in current standards as reliability and probability of failure respectively and is implemented in safety concepts.

Safety concepts in construction ensure sufficient ultimate load-bearing capacity, serviceability, and durability of structures, but also legal protection for the engineers involved. Safety concepts are formulated and implemented in standards and guidelines. These provide both, limit values and verification tools for meeting the required properties. The tools can be of computational nature, such as safety elements in verification proofs, or of an organizational nature, such as the four-eyes principle or quality requirements for building materials. The form of the safety concepts can be freely chosen. Different forms can be seen, for example, in the former German standards DIN 1045 (1988) and ETV Beton (Kühn and Haupt 1979) and in the current Eurocodes. The limit values can be determined by political, legal, and administrative procedures such as standardization work, by social discussions, by experience

and avoidance of observed unwanted events or by calculations using risk or life quality parameters.

The process of technical standardization in construction is defined as bringing together technical knowledge to regulate specific products and processes based on knowledge that has been accepted as correct by the professional community. However, technical knowledge is also subject to change, which is called conceptional aging. Standardization is therefore a dynamic process (Schuppener 2009, Faber et al. 2015). Obviously, structures and their material itself also deteriorate.

However, besides material and conceptional aging, approved structures possess a grandfather status which is the right to continue to use a structure that was legally built at a certain point in time, even if it does not meet current standards.

Some questions arise from these preliminary considerations.

- Do we empirically observe different levels of structural safety in terms of collapse frequencies over the decades?
- Is the target reliability level time-dependent – not related to the age of structures - and dependent on the state of knowledge, respectively?

## 2. TIME-DEPENDENT TARGET VALUES

### 2.1. Observations

Initially, only bridges are considered because the data situation there is excellent. Empirical studies show (see Fig. 1) that the collapse frequency of bridges was significantly greater in the 19<sup>th</sup> century than at the beginning of 21<sup>st</sup> century (Proske 2018, 2022). The decrease of the collapse frequency for bridges can also be documented for the last decades, as data from U.S. bridges indicates (Proske 2018, 2022).

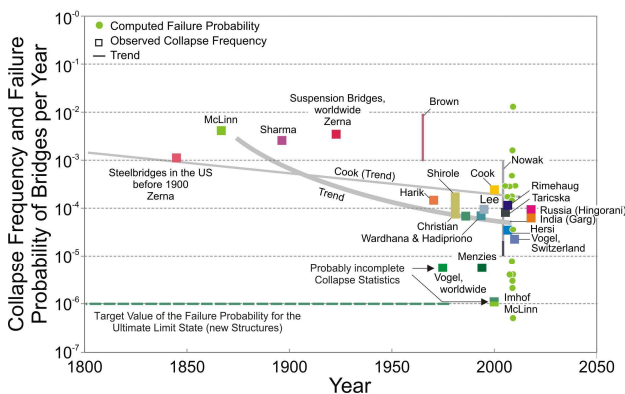


Figure 1: Development of the bridge collapse frequency over time

Numerous publications see fluvial processes as main cause of bridge collapses (Proske 2018, 2022). The July flood 2021 in Germany, with at least 62 bridge collapses, also confirm the statement. Fluvial processes can affect bridges in several ways, e.g., scouring, undercutting, bank erosion, log jams, or debrisflow impacts.

This means that collapse frequencies are also dependent on the very specific location conditions, such as proximity to water or the channel slope. Furthermore, fluvial caused actions are possibly time-dependent due to climate change. This does not apply to earthquake effects, for example which is a major cause of building collapses.

However, it is interesting to note that the absolute number of bridge collapses per year has decreased even in years with large numbers of collapses due to fluvial processes (Proske 2018).

Furthermore, it has been shown that there is a weak correlation between the condition of a bridge and its vulnerability to some natural hazards. Thus, maintenance would not be decisive for the failure of bridges by fluvial processes, but the initial conditions during design and construction. This is also confirmed by the change in the causes of collapse over the age of the bridges: while failures due to fluvial processes occur practically evenly distributed over the entire lifetime of the bridges, failures due to overloading tend to occur at an older bridge age. Thus, maintenance can play an important role for some causes of collapse. Due to the potentially higher casualty rates for collapses caused by traffic loads as opposed to collapses caused by fluvial processes, the former receives more public attention (Proske 2018, 2022).

Besides the mentioned collapse causes, bridge collapses due to lack of quality control, poor design, accidents, and unknown causes were dominant in earlier times: For example, lack of knowledge fell from over 50 % as a cause of collapse before 1900 to virtually zero today, and natural hazards rose from a former 5 % to 30 % (Imam & Chryssanthopoulos 2012). Additionally, collapses depend heavily on the level of training of skilled personnel. Thus, different causes of building collapses can be observed in developing countries and developed industrialized countries even using the same codes but observing different qualification levels. Thus, the causes of collapse are time- and are norm-dependent but not exclusively.

The current state of knowledge for building and bridge collapses can be summarized:

- The absolute and relative number of collapses is decreasing both in short and in long term.
- The vast majority of collapses are caused by large scale accidental actions (for bridges fluvial processes, for buildings earthquakes).
- Poor design, poor quality control, etc., play a minor role today in developed industrialized countries compared to developing countries and earlier times.
- The condition of historic structures is hardly decisive for their resistance to some natural

hazards; the original design is much more important in this respect.

- Bridge collapses due to overloading tend to occur at older ages, collapses due to impact at younger ages, and collapses due to natural hazards are equally distributed across ages.

## 2.2. Comparison with normative target values

Based on this level of knowledge, the question arises as to what the target safety level of previous construction standards was. One can indeed examine the safety level of structures via the development of standards. However, the results are contradictory: There are publications showing equivalent safety targets of historical reinforced concrete standards on bending (Weber 2013, Bures 2020). At the same time, the historical standards show deficiencies in other areas, such as shear force or prestressing (Hars 2006, Wüstholtz 2016).

These differences become even more apparent in the load assumptions. For seismic actions, there are very detailed studies on the development of the standards. For example, according to Wenk (2021), building structures have been designed for earthquakes in Germany since about 1960 and in Switzerland since 1970. From today's point of view, however, earthquake design has been sufficient only since 2003, which means that in Switzerland only about 15 % of the approximately 2.5 million structures would be sufficiently designed for earthquakes. Or to put it another way: since 2003, almost 2.1 million structures in Switzerland would have to be retrofitted to reach current load levels. Assuming the value of real estate in Switzerland to be 1.55 trillion euros and the cost of retrofitting to be 3 to 10 % of the cost of new construction, this translates into a two- to three-digit billion-euro amount.

For earthquake effects, comparisons of the behavior of structures measured by means of historical and current standards exist (Wenk 2005, Bachmann 1997). These prove a lower number of collapses and less damage to structures designed according to new standards.

Similar developments regarding increasing amounts exist for other actions. For example, for

the river Elbe it is proposed to increase the design flood from 4 000 m<sup>3</sup>/s to 4 545 m<sup>3</sup>/s due to the extreme floods in 2002, 2006, 2011 and 2013. The effect of time-limited data series for the determination of design values in the form of low values has been pointed out for years, especially in Switzerland (Wetter et al. 2011).

If the target safety in the historical standards was comparable to current standards, but the former standards did not reach the current verification density nor action intensities, the temporal development of the collapse frequencies as shown in Fig. 1 is plausible.

However, it must be considered that the structures usually undergo maintenance or repair. The structures thus reflect a mixture of different standards. Fig. 2 shows the year of construction and the time of the last maintenance for various bridges of the Swiss Federal Railways.

The evaluation of collapse frequencies of road bridges due to live loads in Italy compared to road bridges in other European countries shows significant differences that cannot be attributed to different standards, but probably to poor maintenance. This has implications for the interpretation of Fig. 1, which thus show not only a decreasing collapse frequency in parallel with the increasing level of development of the standards, but also improved maintenance planning and implementation.

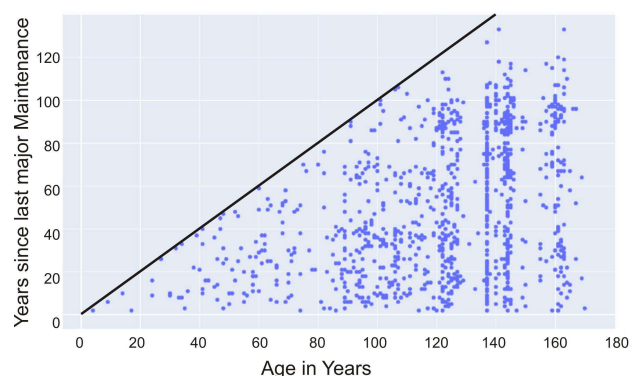


Figure 2: Age versus years since last major maintenance for bridges of the Swiss Railway (SBB)

### 3. STRUCTURAL STANDARDS

#### 3.1. Comparison of Development of Standards versus Collapse Frequencies

The process of technical standardization was already introduced in section 1. In general, standards show an ever-increasing density and number of specific regulations. This is occasionally criticized as overregulation.

The development of standards for reinforced concrete construction in Germany has been described, see Fig. 3. If the curves in Fig. 3 are mirrored around the  $x$ -axis, a curve similar to that in Fig. 1 is obtained. Then the development status of the standard would be inversely proportional to the collapse frequency per year.

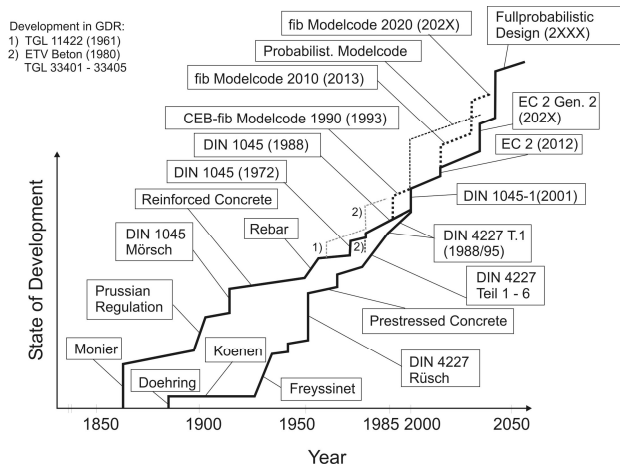


Figure 3: Development of the German Codes for Reinforced and Prestressed Concrete

#### 3.2. Comparison of Development of Standards versus Collapse Frequencies

As already mentioned, the normative safety of structures is composed of a share of computational verifications and a share of other measures. The safety due to computational verifications shall be referred to as explicit safety. For the safety outside of the computational safety verifications, a different term shall be discussed. The term implicit safety has been used by Baravelle and Köhler (2017). Teichgräber et al. (2022) have used the term hidden safety.

The term implicit includes inherent properties of a thing that are either not directly linguistic or not directly formally detectable. Often this property is also perceived unconsciously. From these considerations, the term implicit safety is proposed for safety that does not result from computations.

The author assumes that explicit safety has increased, for example by experimental ultimate load testing and the development of conformance criteria.

The collapse frequency is able to capture both, implicit and explicit safety.

### 4. MACROSCOPIC SAFETY EVALUATION

#### 4.1. Introduction of Parameter

The following theses are assumed:

- There is a relationship between the normative safety of structures and their collapse frequency.
- It is assumed that the collapse frequency captures both implicit and explicit safety.
- The explicit normative safety can be expressed by the operational failure probability.
- Therefore, the ratio of collapse frequency and failure probability is a parameter for implicit safety.

In the following, the ratio of the median of the calculated failure probabilities per structure and the median of the observed collapse frequencies is introduced for different structural types (see Table 1). The parameter is interpreted as an average global implicit safety parameter since no safety elements are included.

The ratio is a macroscopic description of the safety of the structures, which are described at the normative level using meso-models. Meso-models are, for example, bending analyses using the tensile strength of the steel and the compressive strength of the concrete. Micro-models as another class of models would, for example, use parameters for the hardened cement paste, aggregate, and concrete bond strength.

Construction standards are essentially based on meso-models. For this purpose, tensile, flexural, shear or other tests are performed on specimens or structural members. The test results are compared with models, occasionally theoretical, mostly empirical regression models, and the models are adjusted to the observations. Due to simplifications in the tests, e.g., the use of flexural beams without slab superstructures or the neglect of restraints, the tests do not represent the real structure, but are sufficiently accurate and usually conservative. Nowadays, these reserves can become visible due to test loads on real structures.

Table 1: Ratio of median probabilities of failure versus collapse frequencies. (Buildings – no collapses of single earthquakes considered, then ratio

| Type                 | Probability of Failure | Collapse Frequency    | Ratio |
|----------------------|------------------------|-----------------------|-------|
| Bridges              | $2.00 \times 10^{-4}$  | $1.17 \times 10^{-4}$ | 1.71  |
| Dams                 | $3.46 \times 10^{-4}$  | $3.02 \times 10^{-4}$ | 1.15  |
| Tunnels              | $5.30 \times 10^{-4}$  | $2.15 \times 10^{-4}$ | 2.47  |
| Retaining Walls      | $1.35 \times 10^{-3}$  | $8.14 \times 10^{-4}$ | 1.66  |
| Buildings            | $1.06 \times 10^{-5}$  | $3.30 \times 10^{-6}$ | 3.21  |
| Stadiums             | $2.80 \times 10^{-4}$  | $3.30 \times 10^{-5}$ | 2.50  |
| Wind Turbines        | $1.23 \times 10^{-4}$  | $9.40 \times 10^{-5}$ | 1.31  |
| Nuclear Power Plants | $2.04 \times 10^{-5}$  | $2.31 \times 10^{-5}$ | 0.88  |

Today, relevant parameters are mostly identified by so-called statistical correlation measures. However, it is well known that correlations are not necessarily evidence of a functional relationship. For example, one could try to make the macroscopic description of the safety of structures using other than the usual technical parameters in the standards. Such parameters could be the age of technology, age of type of structures, mean extent of damage per event, estimated number of type of structures, mean cost of new construction and other parameters. If the parameters are normalized, one can combine these parameters with the median of the calculated failure probability to obtain the median collapse probabilities.

These parameters would then be an indirect measure of implicit safety on a macroscopic scale. Values for these parameters are given in Table 2.

One can, based on the databases of collapses of certain types of structures, statistically identify these general parameters. Such investigations have been carried out by the author. It was first started with bridges, because there the data is good in comparison with other types of structures.

Table 2: Selected global factors for the several types of structures.

| Type                 | Stock       | Age of Technology in Years | Exposition Time per Year |
|----------------------|-------------|----------------------------|--------------------------|
| Bridges              | 5 250 000   | 6 000                      | 30 h                     |
| Dams                 | 950 000     | 5 000                      | 20 h                     |
| Tunnels              | 125 000     | 4 000                      | 100 h                    |
| Retaining Walls      | 65 000 000  | 6 000                      | 100 h                    |
| Buildings            | 2.0 Billion | 10 000                     | 6 000 h                  |
| Stadiums             | 5 000       | 2500                       | 50 h                     |
| Wind Turbines        | 450 000     | 4 000 (200)                | 5 h                      |
| Nuclear Power Plants | 600         | 70                         | 0                        |

However, one can also link the parameters for converting the failure probabilities into collapse frequencies to the exact verification equations. This would show the implicit safety at the level of the verification formula. This would allow linking these considerations with usual research.

#### 4.2. Development over Time

Fig. 4 visualizes the data from Tables 1 and 2. Based on Fig. 4, it can be hypothesized that a curve exists on which the structures migrate, from the upper right quadrant to the lower left quadrant. This curve is already shown in Fig. 5. The drift away from the diagonal in the lower left quadrant is probably due to larger relative errors in the calculations at such small probabilities.

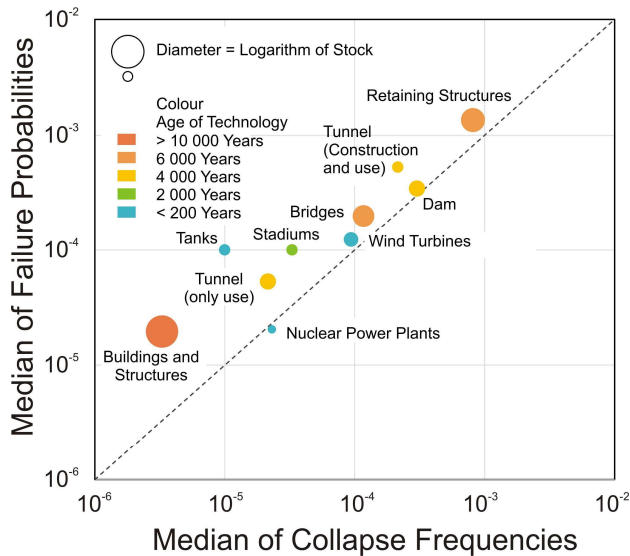


Figure 4: Visualization of values from Table 1 and 2

However, there is a considerable spread of values and thus the uncertainty of this consideration. Further subdivisions are needed here. It is also known that the quality of the data shows differences depending on the type of structure.

Based on the available data, a rate of change of collapse frequencies can be given. This is listed in Table 3 for different types of structures. The large rate of change for nuclear power plants results to a not insignificant extent from extrapolation to 100 years.

If one follows the thesis of a change, the following task is to choose a function in Fig. 4. However, the representation is strongly simplified. The curve probably does not follow a linear or quadratic function, but a time-dependent hysteresis or an extended cycloid. This can be justified by the fact that safety usually evolves in a cyclic function: States alternate between safe and unsafe.

Such cycles can also be demonstrated concretely for bridge construction. For example, it is well known that in France, starting in 1830, there was a euphoria for the construction of cable bridges. Within a few years, more than 200 such bridges were built. The collapse of the Basse-Chaîne bridge in 1850 with over 200 fatalities put an end to this euphoria. A second example are several collapses of steel box girder bridges in the late

1960s/early 1970s. Again, there was some euphoria for the new technology, which was disillusioned by several collapses. Current ones would be the boom of wooden bridges, the collapse of the Tretten wooden bridge, and the precautionary closure of 14 wooden bridges in Norway.

The impact of such collapses on standardization has been discussed in Birdgale & Sims (2009), Ratay (2010), among others.

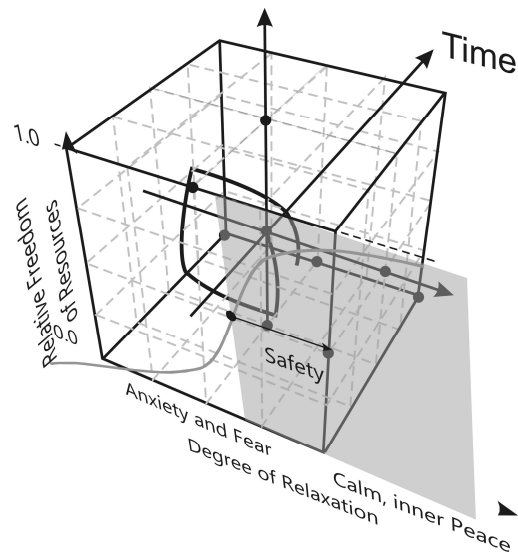


Figure 5: Theory of Safety as Relative Freedom of Resources (Proske 2009).

If we combine Fig. 4 with the hypothesis of cycles (Fig. 5), we come to the Fig. 6. It is also shown that the nuclear power plants move towards the main axis. Thereby the speed is relatively high (see Table 3).

Table 3: Factor of extrapolated decrease of collapse frequency per century.

| Type                 | Decrease of Collapse Frequency per Century by |
|----------------------|-----------------------------------------------|
| Bridges              | 4.68                                          |
| Dams                 | 10.96                                         |
| Tunnels              | 4.07                                          |
| Nuclear Power Plants | 204.17                                        |

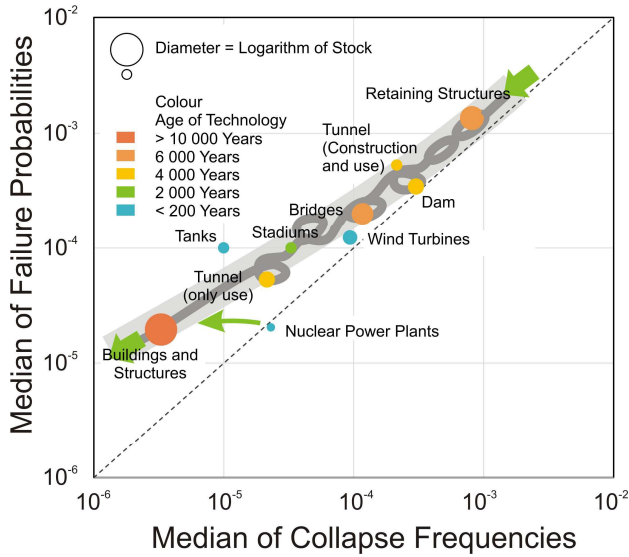


Figure 6: Visualization of values from Table 1 and 2

Whether the cycles will become smaller is doubted by the author. New, additional requirements, influence safety because they create new, often unknown, and underestimated hazards. For example, wooden constructions, which are increasingly promoted for sustainability reasons, will show different effects on safety than concrete constructions, which have been successful for a long time. Such effects may include fire protection, moisture protection, and mass distribution in buildings. The same applies to new slender concrete structures, e.g., made of carbon concrete. And this is especially true for the provoked digitalization. All these developments are, to a certain extent, helpful and necessary. But they involve hidden changes in normative assumptions that directly or indirectly affect safety. Therefore, utmost vigilance is required, especially when introducing new technologies.

Political influences on the short-term introduction of technologies play an important role. We need only refer to the “Nuclear for Peace” program, the influences of political decision-makers on the experiments that led to the Chernobyl disaster, or the introduction of the Space Shuttle.

## 5. OUTLOOK AND CONCLUSION

This paper has presented a variety of theses, some of which are based on previous work, some of which would still need to be proven, and some of which involve considerable simplifications in order to take a different look at safety of structures. In this respect, further research is needed.

A possible work step for future statistical studies of collapses and consideration of probabilities of failure would be to use of data for the respective actions. If floods are by far the largest cause of bridge collapses, then one would need to see better design for floods in years with events. Such studies have already been carried out for earthquakes.

One must further distinguish in the collapse data between structures in their original condition and structures after, possibly several, maintenance and strengthening measures.

However, it can be shown, that structures on average show a greater safety than the calculated safety. This margin is referred to as implicit safety. This implicit safety is not only a consequence of a tighter verification concept, but also of quality assurance measures and conservative assumptions. This safety may be used in the evaluation of existing structures.

Based on the above, the following conclusions are drawn:

1. The collapse frequency of structures in general and bridges in particular is decreasing with time, both over centuries and decades.
2. Standards show an increasing level of development over the decades and centuries, with a higher density of verification and higher quality requirements. The target safety level for standards from different times does probably differs only slightly.
3. Based on point 2, a grandfathering can be justified. Nevertheless, various computational actions on structures have increased considerably. For the effect of earthquakes, it is known that structures based on old standards behave significantly worse than structures based on new standards.

4. The safety of structures is divided into an explicit and implicit part. The explicit part includes the safety elements in computational verifications, while the implicit part includes all non-computational safety measures.
5. The ratio of the median failure probabilities and the median collapse frequencies is approx. 2 (see Table 1). Both global and structure type-specific parameters can be statistically identified to explain this difference.
6. There is a curve of the development of the collapse frequency to failure probability ratio for all types of structures, probably even for all engineering products.
7. This curve is followed in cycles to smaller and smaller failure values. The speed at which the structure types move along the curve varies.
8. The use of collapse frequency as a parameter for testing the safety of structures is still under discussion.

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