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COMPARISON OF THE COLLAPSE FREQUENCY AND FAILURE PROBABILITY OF BUILDINGS

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Abstract.

In a previous study, the collapse frequencies and associated mortalities of buildings were compiled based on various publications. The investigation showed a considerable scattering of collapse frequencies depending on the countries. In this paper, the collapse frequencies determined for buildings are compared with the results of probabilistic calculations. Such comparisons have already been carried out for bridges, dams, tunnels and retaining walls including the consideration of central estimators and standard deviations. In order to limit the scatter, the probabilities of failure for buildings were subdivided into the different causes of failure, and collapse frequencies were subdivided into different countries and geographical regions. Overall, the comparison shows that the probabilities of failure are on overage larger than the observed collapse frequencies. Furthermore, the comparison shows are large span, which is unusual for other types of structures. Of concern are the high observed collapse frequencies in various developing countries. Human error, lack of training, etc. are often cited as the cause. Should this correspond to the facts, the basic safety concept of modern building standards, which generally excludes human error, would only be applicable in these regions to a limited extent. However, the investigation includes some limitations, such as different safety targets in different standards and different years of constructions, which are not considered. Further work is required.

Keywords: Buildings, collapse, collapse frequency, probability of failure.

1. Introduction

Modern safety concepts for structures are based on probabilistic models [1, 2]. In contrast to these calculation models, in which either directly or indirectly nominal failure probabilities are determined, there are the observations of building collapses. Whether and how the calculated and observed values are comparable and related, is the subject of scientific discussion [3, 4]. Comparison is common in other disciplines [5, 6], but is often rejected in the construction industry [1, 2].

Nevertheless, the calculated failure probabilities and the observed collapse frequencies of bridges [7], dams [8], tunnels [9] and supporting structures [10] were compared within the framework of a series of articles. Furthermore, the comparison was also methodologically extended from central estimators to statistical uncertainty parameters [11]. Also, the mortality due to structural collapses was estimated, see for example [9, 12].

This document presents the comparison of collapse frequencies and failure probabilities for buildings. In the following section the term building is defined.

2. Definition of Buildings

Structures can basically be divided into two classes:

- Buildings as residential, commercial, and public buildings as well as buildings for the sports and leisure sector.
- Civil engineering structures as part of the infrastructure such as bridges, dams, retaining walls and tunnels.

This paper focuses on buildings. Three definitions of buildings are given.

The German Federal Statistical Office [14] defines buildings as: "*…structures that generally rise substantially above the earth's surface. For technical reasons, buildings also include independently usable underground structures that can be entered by people and are suitable or intended for the protection of people, animals or property (e.g., …., underground shopping centres and production facilities, underground car parks)*".

The Swiss Confederation [15] defines: "*Buildings [are] a permanent structure, provided with a roof, firmly attached to the ground, capable of accommodating persons and serving residential purposes or purposes of work, education, culture, sport or any other human activity; …*"

The Free State of Saxony [16] in Germany defines: "*Buildings are independently usable, covered structures that can be entered by people and are suitable or intended to serve the protection of people, animals or*

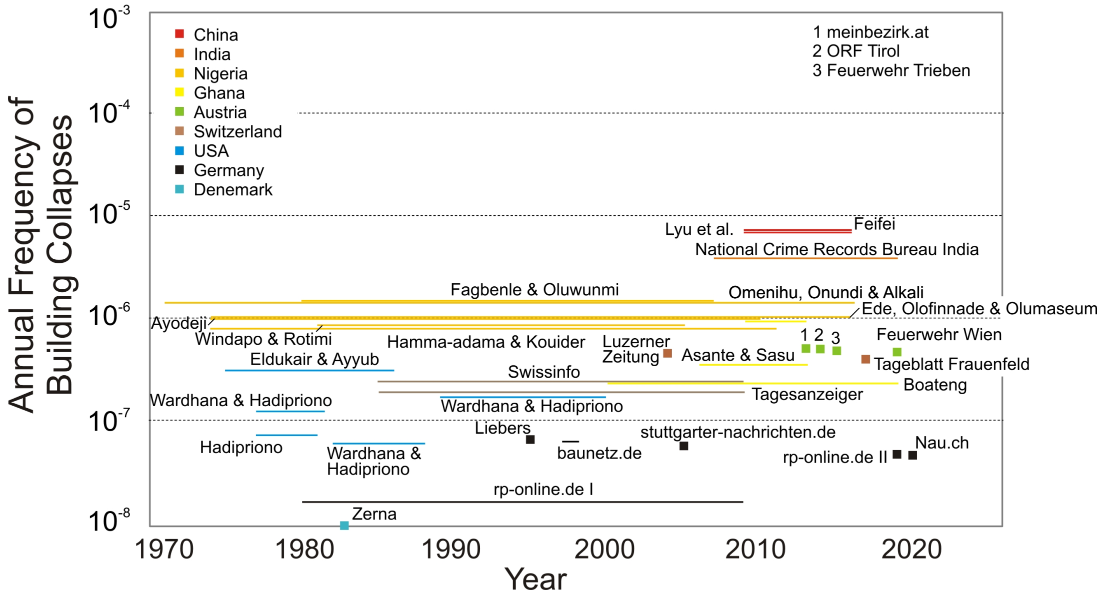

Figure 1. Annual frequency of building collapses based on [13]. The individual references are given in [13].

property."

3. Definition of Collapse and Failure

After the definition of the term building, the terms collapse and failure should be defined.

Usually, a collapse is a sequence of failures of structural elements leading to the destruction of the building (non-repairable). The sequence is often described as chain reaction and progressive collapse. Collapse frequencies are computed based on observed and documented collapses of buildings. Another definition considers the building collapse as the entire structure or parts come down.

In contrast, failure is the computational exceedance of a single ultimate limit state equation, which may or may not yield to a non-repairable damage. This exceedance of the ultimate load state equation is related to one internal force (moment, shear force, axial force, buckling etc.) and one location at a structural element. Probabilistic failure computations are related to numerical models incorporating random variables as well as individual limit state functions. The results of individual probabilistic computations for one structural element and one limit state can be combined to consider the entire structures.

4. Collapse Frequency of Buildings

The collapse frequency is computed as follows:

$$F = \frac{n_C}{n_B} \tag{1}$$

The stock of buildings n_B, the number of collapses n_C and the collapse frequencies of buildings F were investigated and visualized in [13] based on a large number of publications. This reference also includes the investigation of the mortality due to building collapses. However, the study does not include collapses from earthquakes and floods.

Figure 1 gives an overview of references related to the collapse frequency of buildings and Figure 2 shows the mortalities based individual references. The individual references are given in [13].

5. Probability of Failure of Buildings

While only a relatively small number of publications can be used to determine collapse frequencies, there is an almost unmanageable number of publications with calculations of the probability of failure of buildings. In the context of this study, 22 publications were selected, however finally only 21 are used. The publications refer to a wide range of actions, but they are not yet a representative selection of the building stock. The discussion of the assumptions and limitations of each of the used publications is beyond the scope of this article. Even further, the study should be extended using more references and distinctions of the building stock.

Table 1 and Figure 3 visualises the probabilities of failure of the used references. Furthermore, Figure 3 includes the observed collapse frequencies from Figure 1 in grey colour. Additionally, the references of the collapse frequencies have been excluded.

6. Discussion

Based on Table 1 and Figure 3, it can be seen, that the probabilities of failure show an extraordinary scatter. The values range 10^{-19} to 10^{-1} per year. The scatter

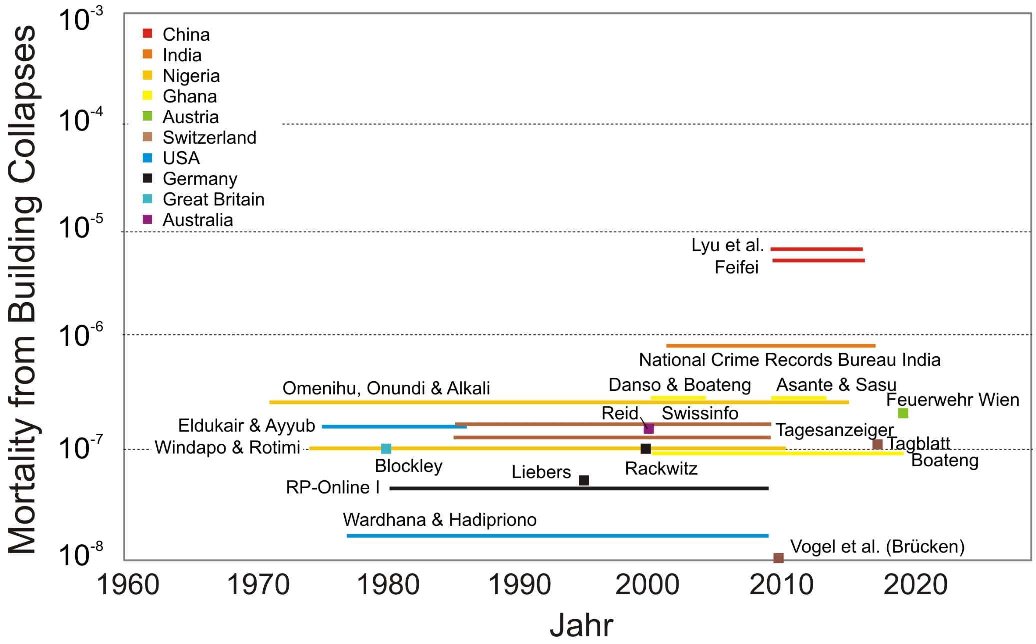

FIGURE 2. Mortality due to building collapses based on [13]. The individual references are given in [13].

Number	Reference	Action	Range of Probability of Failure
1	[17]	Structural Analysis	3.17×10^{-5} to 9.68×10^{-4}, 6.21×10^{-3} to 2.12×10^{-1}
2	[18]	Snow	3.17×10^{-5} to 1.39×10^{-2}
3	[19]	Earthquake	1×10^{-5} to 1.05×10^{-2}
4	[20]	Earthquake	9.87×10^{-10} to 1.07×10^{-2}
5	[21]	Structural Analysis	3.47×10^{-3} to 6.87×10^{-4}
6	[22]	Wind	6×10^{-4} to 8×10^{-4}
7	[23]	Earthquake	$0.310 \times 10^{-2}/0.363 \times 10^{-2}$
8	[24]	Human Failure	0.3×10^{-3} to 1.3×10^{-3}
9	[25]	Structural Analysis	8.275×10^{-6} to 1.285×10^{-5}
10	[26]	Human Failure	1.35×10^{-2} to 8.63×10^{-2}
11	[27]	Foundation	1×10^{-6} to 1.3×10^{-4}
12	[28]	Foundation	$4.5 \times 10^{-6}/4.21 \times 10^{-4}/1.86 \times 10^{-8}/2.47 \times 10^{-8}/1.70 \times 10^{-6}$
13	[29]	Wind	1×10^{-5}
14	[30]	Wind, Typhoon	$1.7 \times 10^{-4}/1.69 \times 10^{-3}$
15	[31]	Earthquake	3.4×10^{-4} and 2.8×10^{-3}
16	[32]	Wind	1.0×10^{-6} to 5.58×10^{-5}
17	[33]	Foundation	$2.72 \times 10^{-8}/1.22 \times 10^{-9}/1.61 \times 10^{-11}/1.89 \times 10^{-16}$
18	[34]	Fire	$3.8 \times 10^{-7}/7 \times 10^{-10}$
19	[35]	Human Failure	6.4×10^{-6}
20	[36]	Fire	$3.3 \times 10^{-9}/3.3 \times 10^{-8}$
21	[37]	Structural Analysis	1×10^{-5}

TABLE 1. References and related Probabilities of Failure.

is significantly larger than the scatter of the collapse frequencies.

Furthermore, the probabilities of failure are on average clearly above the average of the collapse frequencies. Of course, the collapse frequencies in Figure 1 and 3 do not consider large-scale accidental actions such as earthquakes or floods, which are considered in the probabilities of failure. Whereas the median of the probabilities of failure without accidental actions is in the range of 1.06×10^{-5}, the median of all results is in the range of 6×10^{-4} per year.

The collapse frequency on a worldwide scale without earthquakes and floods was 3.3×10^{-6} per year [13]. Own estimations considering earthquakes and floods yields to a factor 3 to 20 for this collapse frequency, either based on Table 2 and 3 or on the average number of fatalities due to earthquake and the number of collapsed buildings [39, 40]. This would yield to a

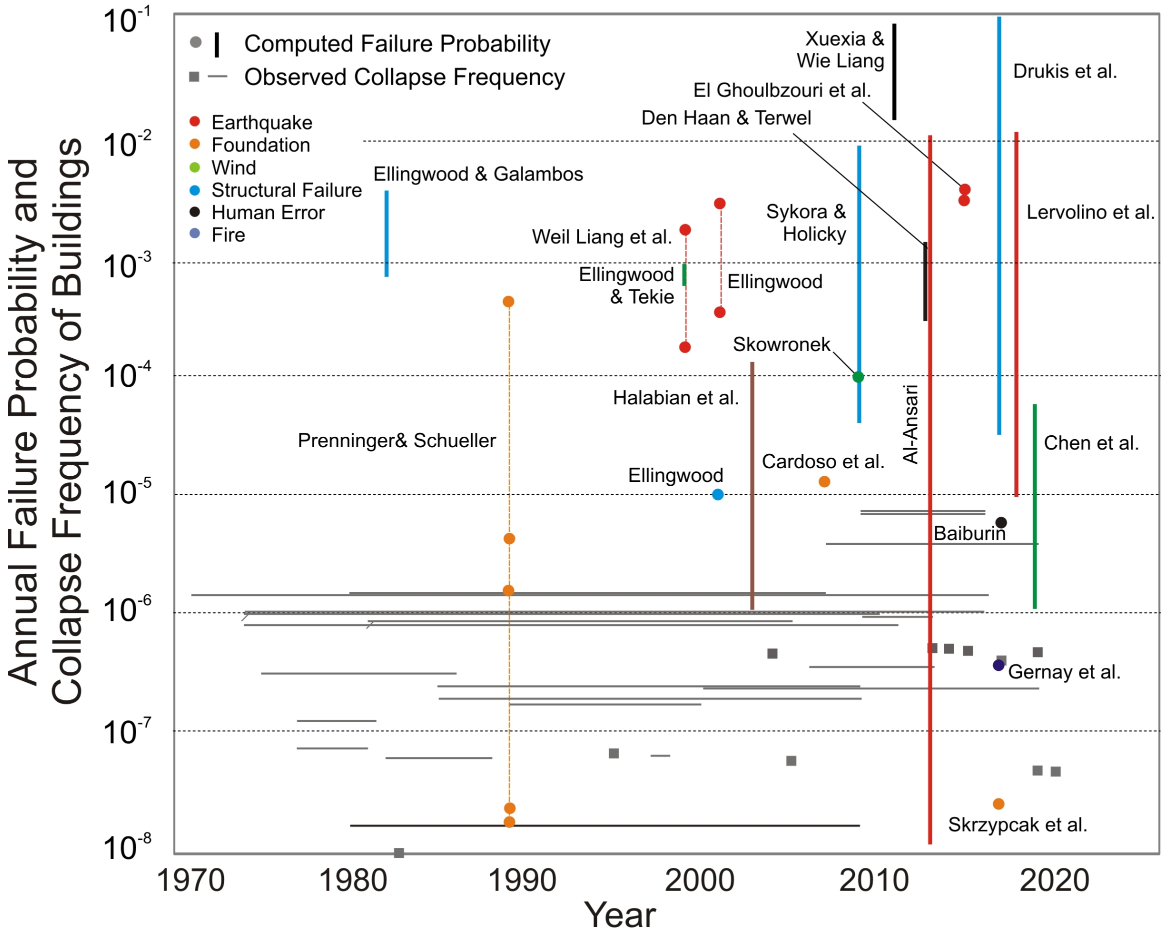

Figure 3. Computed probabilities of failure for buildings based on various references given in Table 1 and related to actions.

Year	Country	Action	Number of buildings destroyed
1970	Bangladesh	Flood	400,000
1995	Kobe, Japan	Earthquake	46,000 - 100,000
2001	El Salvador	Earthquake	200,000
2001	Peru	Earthquake	20,000
2004	Southeast Asia	Tsunami	300,000
2010	Haiti	Earthquake	250,000
2011	Japan	Earthquake and Tsunami	45,000 - 130,000 destroyed 190,000 - 240,000 damaged

Table 2. Number of destroyed houses during large-scale accidental actions.

Year	Damaged houses	Destroyed houses	Collapse Frequency	Ratio to 3.3×10^{-6}
2015	660,000	85,000	6.5×10^{-5}	19.81
2016	380,000	90,000	6.9×10^{-5}	20.98
2017	560,000	115,000	8.8×10^{-5}	26.81
2018	450,000	95,000	7.3×10^{-5}	22.14
2019	340,000	90,000	6.9×10^{-5}	20.98
2020	170,000	30,000	2.3×10^{-5}	6.99

Table 3. Number of damaged and destroyed houses during earthquakes per year worldwide (Earthquake Impact Database). The total stock of buildings has been assumed with 1.3 billion, which is slightly below 1.5 used in [38].

collapse frequency in range from 1×10^{-5} to 7×10^{-4}.

Therefore, the ratio of median probabilities of failure to median collapse frequencies is 3.2 ($(1.06 \times 10^{-5})/(3.3 \times 10^{-6})$) without considering earthquakes and floods. For the consideration of earthquakes and floods this ratio would be in the range just below 1 to well over 20 with an average value in the upper range ($(6 \times 10^{-4})/(1 \times 10^{-5}$ to $7 \times 10^{-4})$.

The large span of the difference between the calculations and the observations stays in contrast to all other types of structures, such as bridges, dams, retaining structures. For those the values are in the range of 2. On the other hand, buildings form the largest number among the structures. Therefore, subgroups have probably to be formed to increase the quality of this comparison, especially with focus on earthquakes. Even further, we have not considered the different target values in different standards, such as ASCE and Eurocode, the different consequence classes, and the different construction years of the buildings and the relevant standards. It is well known that newer standards yield to better structural behaviour under extreme loads such as earthquakes. These distinctions can be investigated in future works.

On the other hand, this study shows that the computed probabilities of failure in average are conservative.

7. Conclusion

The sample size of the publications used for the investigation of the failure probabilities and the collapse frequencies is roughly comparable. However, the differences between the average calculated failure probabilities and the observed collapse frequencies shows an large span, which is in contrast to other types of structures. For this reason, further work is necessary, such as

- increasing the number of considered probabilistic calculations,
- selection of probabilistic calculations representative for the building stock,
- more precise interpretation of the ranges of failure probabilities in the publications,
- assign the collapses and calculations to specific actions (earthquakes),
- comparison of specific types of buildings or country specific buildings with the related computation and,
- distinction of the collapsed buildings with regards to construction year, used code and used target values.

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