Risk Analysis and the Acceptable Probability of Failure

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Introduction

Risk analysis is a useful tool for the practising structural engineer to make rational decisions when designing for accidental loads. The author's experience relates to ship collision with bridges, but the main aim of this paper is to discuss the acceptable probability of failure for structures and to highlight a possible mismatch between the accepted risk for variable loads and accidental loads. Variable loads are defined as a load for which the variation in magnitude with time is neither negligible nor monotonic. For example wind loading and highway loading on a bridge are variable loads. Accidental loads are usually of short duration but of significant magnitude and are unlikely to occur over the lifetime of the structure.

Reliability based calibration of codes for variable loading is a generally accepted procedure. An important starting point is to select the appropriate value for the target reliability of structures. For the development of codes different methods have been proposed for estimating target reliabilities such as calibration to existing codes, comparative risk of failure and economic optimisation. These approaches are possible for variable loads where sufficient statistical information is available, though the analysis can become very complex and inconsistencies still remain in existing codes. For many reliability based codes the most straightforward approach is calibration to existing codes. This is based on the presumption that structures in service today have an acceptable level of safety against structural failure.

Is there a problem?

It is pertinent to ask whether there is a problem. A study by PIANC[1] published in 2001 attempted to collate data on ship collisions. This study collected data on 149 collisions that occurred worldwide in the period between 1960 and 1996. Many countries and port authorities have only recently started collecting data on ship collisions, so the data is skewed towards the latter years, however the study identified what was defined as "very serious accidents" which were accidents that were estimated to cost over US$ 1 Million. The data included 22 very serious accidents, which gives an average rate of 0.6 very serious accidents worldwide per year. The accident rate has shown a slight decrease since a peak in the 1970's but essentially the rate has been remarkably consistent over the past four decades. Over this period over 300 people have died in these accidents and large economic losses have been incurred in repair/replacement costs, lost transportation service and other damages.

Given the large number of bridges exposed to such accidental damage, one may conclude that ship collision is not a major cause of damage to bridges, but it has enough significance that it should be taken into account in the design of all bridges. It is suspected that similar conclusions can be drawn for other accidental loads, but it still leaves the question of how to assess the risks and what the acceptable probability of failure should be.

Risk Analysis

A risk analysis may take the form of either a qualitative or quantitative analysis. Once the analysis has been completed a risk management exercise should be undertaken to define whether certain risk acceptance criteria have been met and what measures should be undertaken to mitigate against the risks. The risk management exercise might lead to reconsideration of the overall design concept. A risk analysis will rely on the judgement of the engineer and may for that reason differ from the actual risk of failure, however it is a useful tool to enable the designer to make rational decisions in the design for accidental loads. Numerous papers have been published on the methodology for quantitative risk analysis for ship collisions. In particular guidance has been published by AASHTO and will shortly be published in Eurocode 1 Part 1-7: General Actions – Accidental Actions[2].

In the United States the collapse of the Sunshine Skyway Bridge crossing Tampa Bay in Florida was a major turning point in the design of bridges for ship collision. This bridge was struck by a 35,000 dwt bulk carrier causing the collapse of the southbound main span and the loss of 35 lives. Following this collision AASHTO published a Guide Specification and Commentary for Vessel Collision Design of Highway Bridges.[3] This document was based on the published data from the "1983 Colloquium on Ship Collisions with Bridges and Offshore Structures" held in Copenhagen by IABSE.

A study has been undertaken to compare the collision rate estimated by the AASHTO Guidelines for vessels entering the Port of London with the actual collisions that have occurred. Over a period of six years from 1991 to 1996 there have been 21 recorded collisions with bridges, which give an annual rate of 3.5. Only one of these collisions caused serious damage to any of the bridges. The AASHTO Guidelines give an estimated collision rate for the number of bridge passages per annum of 5, which gives good agreement with the recorded collisions. This gives a limited degree of confidence in the use of risk analysis to identify the risk from ship collision.

Probability of Failure

The final project draft of Eurocode 1 Part 1-7 has a useful note that summarises the approach that should be taken in designing for accidental actions:

> "In practice, the occurrence and consequences of accidental actions can be associated with a certain risk level. If this level cannot be accepted, additional measures are necessary. A zero risk level, however, is unlikely to be reached and in most cases it is necessary to accept a certain level of residual risk. This final risk level will be determined by the cost of safety measures weighed against the perceived public reaction to the damage resulting from the accidental action, together with consideration of the economic consequences and the potential number of casualties involved. The risk should also be based on a comparison with risks generally accepted by society in comparable situations."

The code goes on to say that the level of acceptable risk may be given in the National Annex. An earlier version of this code gave advice that in the absence of quantification of consequences and economical optimisation, a failure probability of 10^{-4} per year seems to be appropriate for accidental actions. However, possibly quite wisely, the final project draft does not give any such advice.

A number of published documents give recommendations for failure or load criteria and these are as follows:

ISO Dp 10252 Accidental actions due to human activities[4]

The representative value of the accidental action should be chosen in such a way that there is an assessed probability less than 10^{-4} per year for one structure that this or a higher energy will occur.

AASHTO Guide specification and commentary for vessel collision design of highway bridges[3]

CRITICAL BRIDGES. The acceptable annual frequency of collapse, AF, of critical bridges shall be equal to, or less than, 0.01 in 100 years giving an annual frequency of 10^{-4}.

REGULAR BRIDGES. The acceptable annual frequency of collapse, AF, of critical bridges shall be equal to, or less than, 0.1 in 100 years giving an annual frequency of 10^{-3}.

Ship collision with bridges – The interaction between vessel traffic and bridge structures. IABSE Structural Engineering Documents,1993[5]

An order of magnitude for the acceptable probability of bridge disruption of 0.1 – 0.01 in 100 years may be derived.

It is believed the ISO criterion is often quoted for the design against explosions, It is worth noting that this criterion is with respect to the design load rather than structural failure, however as discussed later there may not be a significant difference between the probability of the load and the risk of failure. The AASHTO and IABSE criteria were developed from the conference in Copenhagen so it is unsurprising that they are similar. The AASHTO guidelines are of some significance as a large proportion of the accidents have occurred in the United States and there are a large number of vulnerable bridges in the United States. It is believed that these guidelines are probably the most regularly quoted by practising engineers worldwide.

All of the above give similar magnitudes for the acceptable failure criteria of approximately 10^{-4} for important bridge structures. This gives a 1% probability of failure for a 100 year life of the structure, which seems high. Another more general social criterion is as follows:

Rationalisation of Safety Factors and Serviceability Factors in Structural Codes CIRIA Report 63[6]

A rational target total risk of failure might therefore be taken as:

$$P_{ft} = \frac{10^{-4}}{n_r} K_s n_d$$

where P_{ft} is the probability of failure due to any cause during the design life n_d years, n_r is the number of people at risk in the event of failure and K_s is given the following values:

Places of public assembly, dams	0.005
Domestic, office or trade and industry	0.05
Bridges	0.5
Towers, masts offshore structures	5

This criterion was used for the design of the Second Severn Crossing and lead to the definition of the ship impact loads for the design. The aim in this instance was to achieve a risk of failure of any one span of less than 4 x 10^{-7} per annum.

Eurocode 1 gives recommended minimum values for the reliability index β for variable loads at the ultimate limit state, for different classes of structure. Reliability Class 1 (RC1) has **low** consequences for loss of human life and economic, social or environmental consequences **small or negligible**. Class (RC2) is **medium** and **considerable**. Class 3 (RC3) is **high** and **very great.**

Eurocode – Basis of Structural Design[7]

Reliability Class	Minimum values for β	
	1 year reference period	**50 years reference period**
RC3	5.2	4.3
RC2	4.7	3.8
RC1	4.2	3.3

The reliability index can be converted into annual failures of probability as follows:

Reliability Class	Annual failure probability
RC3	10^{-7}
RC2	10^{-6}
RC1	10^{-5}

A typical bridge is likely to fall into reliability class 2 and therefore an annual probability of failure of 10^{-6} per annum would appear to be acceptable. A paper by John Menzies[8] proposes a target risk of collapse of bridges less than 20m of 2 x 10^{-6}, which appears to be in close agreement with the annual failure probability quoted in Eurocode 1. It is also worth noting that this paper notes that historically more than half of all collapses are due to accidental impact or scour/flooding.

Selection of Impact Forces

An interesting exercise is to determine the acceptable probability of the design load being exceeded assuming a reliability index β of 4.7. In selecting the design value of accidental effects α_E = -1.0 (or close to –1.0) as σ_E is large when compared with σ_R. Following normal practice for design against accidental loads the material properties should be selected as characteristic values with material factors equal to 1.0. It is assumed that the material properties are defined as follows:

$P(R>R_d) = 0.05$ (5% chance that the material resistance is less than the characteristic value.)

Then α_R can be calculated:

$$P(R>R_d) = \Phi(-\alpha_R\beta) = \Phi(\alpha_R \text{ x } 4.7) = 0.05$$

$$=> \alpha_R = 1.65/4.7 = 0.35$$

For simplicity, if normally distributed variables are assumed, the design point lies on a circle as shown in Figure C2 in Eurocode 1:

$\alpha_E^2 + \alpha_R^2 = 1.0$

$\Rightarrow \alpha_E = -0.94$ (i.e. close to –1.0)

and therefore the action effects (critical impact load) are selected on the following basis:

$P(E>E_d) = \Phi(\alpha_E\beta) = \Phi(-0.94 \times 4.7) = 5.4 \times 10^{-6}$.

This indicates that the probability of the critical impact load being exceeded should equal 5.4 x 10^{-6} per annum, which is not very different to the annual risk of collapse.

Summary

There would appear to be little reason why the basic probability of failure for accidental loads should be any different to the probability of failure for variable loads. However there will be certain circumstances whereby the risk can be allowed to increase. Any increase in risk might be assessed on the basis of a cost benefit analysis, which should be carried out in consultation with the relevant authorities. But in all cases the level of risk should consider whether the risk to human life is acceptable. It is also worthwhile noting that a cost benefit analysis may give a good case for accepting higher risks of failure due to accidental loads rather than variable loads. This is because the shape of the distribution of loads is very different. Thus increasing the resistance of the structure by a small amount might significantly reduce the risk of failure due to say wind loads, but may barely reduce the risk of failure due to accidental loads.

There is another feature that may be considered when one selects the target risk of failure. The values quoted above have been derived for normally occurring variable loads. Society expects a high level of reliability for these types of loads because the engineer should expect that traffic jams will occur and the wind will blow. However, a lower reliability for accidental loads may be accepted, as society understands that the engineer is less able to predict these events and there may be less of an outcry if failure occurs due to an accidental load. Politicians may have the relevant expertise in assessing the acceptable levels of risk that the public might bear.

In conclusion it is proposed that in normal circumstances the engineer should aim for a risk of failure of the order of 10^{-6} per annum, but this can be increased on the basis of a cost benefit analysis and in consultation with the relevant authorities. By reference to a number of past bridge projects an acceptable upper bound on the risk would appear to be 10^{-4} per annum.

References

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6. Rationalisation of Safety Factors and Serviceability Factors in Structural Codes CIRIA Report 63.
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8. Bridge Failures, Hazards and Societal Risk. JB Menzies. International Symposium on The Safety of Bridges. July 1996 London.