7B.6 APPLICATION OF RISK BASED INFRASTRUCTURE DESIGN CONCEPTS TO PROVISION FOR CLIMATE CHANGE

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1. INTRODUCTION

Buildings and the structural systems of infrastructure facilities represent the most important classes of structures designed by civil structural engineers. The interrelationship between these structures and the environment, particularly the climate, range from providing comfort, to protection even under extreme conditions, to actually harnessing resources. In addition to buildings, such facilities include bridges, dams and reservoirs, ports and coastal installations, power stations, towers, for example.

The design of such structures is therefore closely coupled to the climate and the structures are particularly exposed to extreme climatic conditions. In many cases the economic implications of providing protection against climatic extremes have a decisive influence on the feasibility of the facility; often such protection is vital to the safe utilization of facilities.

Increases in the scale of urban and infrastructure development, population at risk and a systematic change in acceptable levels of risk and safety demanded by society, provide strong motivation for improving the rational basis for designing structures against extreme environmental situations and loads.

Reliability based structural design procedures relate probabilities of the occurrence of environmental loads and the resistance of the structures to set levels of reliability. In risk based design, the consequences of failure of the structure are also taken into account.

Probabilistic models of extreme climatic conditions therefore form an important interface between climatology and infrastructure design practice. This interface is of particular importance since uncertainties due to limited knowledge is often comparable to the inherent variability of extreme conditions at probabilities which are significant to structural design. In addition to present needs for improved models for extreme climate, it also now becomes imperative to consider the effects of climate change. This paper provides a review of the way in which extreme weather conditions are factored into structural design. The common interest in probability models for extreme conditions could serve as basis for improving both present practice and provision for the imminent effects of climate change.

A joint review of the status of climate change information for the distinct but complementary conditions of Germany and South Africa serves as background to the present paper (G-SA YoS 2013). The review was made in particular from the perspective of considering the structural performance of buildings and infrastructure in the two countries.

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However, the interaction between climatology and structural design practice is of global interest and relevance. Information on structural design practice should provide useful background to climatologists concerned with extreme climate conditions and how it will change in the future. At the same time the pragmatic view taken by engineers of the complexity and intricacies of the climate should be taken as the reality within which the respective professionals need to engage.

Clear statements on the interrelationship between climate change and infrastructure can be extracted from the *Draft Climate Assessment Report* (NCADAC 2013), such as the case for the reality of climate change, the fact that *the past climate is no longer a sufficient indicator of future conditions*; need to update building codes to *improve protection against extreme events*; many changes that *will be disruptive to society because our institutions and infrastructure have been designed for the relatively stable climate of the past, not the changing one of the present and future*; but also that *using scientific information to prepare for these changes in advance provides economic opportunities, and proactively managing the risks will reduce costs over time.*

Considering the design life of many classes of infrastructure reaching up to one hundred years as for example in case of bridges or tunnels, immediate concerns are raised on the basis of structural design; to a lesser extent also the management, maintenance and performance of existing facilities. Consideration of future performance against the present needs for capital investment is often difficult to motivate under competitive economic conditions.

2. SURVEY: GERMANY & SOUTH AFRICA

The survey on the status of climate change activities and concerns in Germany and South Africa focused primarily on possible changes to extreme environmental conditions, as a critical component of the basis of structural design. This is clearly a special field of investigation. Indications of changes in the frequency and severity of extreme conditions were also investigated. Any adjustments to present design practice to provide for the effects of climate change were noted.

The survey was concluded by reviewing the present treatment of extreme environmental conditions in design practice; considering the way in which adjustment could be made to effectively and optimally provide for climate change in the future. The final step was to identify the needs for further research – by the engineers to refine the rational basis for design; the need for improved quantitative models of extreme climate conditions sought from climatologists.

The results of the survey are reported by Retief et al (2014). Pertinent observations are the following: Present indications of climate change in the two countries are confirmed by observations of the trend of temperature rise. For Germany an increase of 0.8°C to 1°C over the last century is observed; for South Africa the trend is approximately 0.17°C/decade since 1960+ with a high likelihood of the rate increasing. There are clear indications of the increased occurrence of extreme precipitation over the last forty years, but with seasonal and regional differences; flooding of inland waterways in Germany at levels that correspond to return periods of hundreds of years and exceptional storms along the South African coastline. The diversity of the conditions for the respective countries effectively contributed to the broad base of the survey.

3. RELIABILITY BASIS OF STRUCTURAL DESIGN

Design methodologies have been developed to achieve a reasonable balance between functionality, safety and economy of the facilities. Formalized design procedures are based on a combination of experience and judgment on the one hand and reliability or probabilistic and risk optimization methods to provide the complementary rational basis. Reliability based design endeavors to achieve consistent probability of structural failure (P_F) across a range of conditions. Risk based design considers the expected consequences of failure ($P_F \times C_F$) as basis for decision making and design.

According to the JCSS Probabilistic Model Code (JCSS-PMC 2001) and the International Standard ISO 2394:1998 the probabilistic representation of structural performance can be expressed in terms of the following reliability based performance function ($\boldsymbol{g}$) of actions on a structure (E, action effect) and its resistance (R) against failure and the probability of failure P_F, also expressed in terms of the reliability index (β), where Φ is the cumulative Normal distribution function.

$$g = R - E = 0 \qquad [1]$$

$$\mathrm{P_F} = \mathrm{P}(g < 0) \qquad [2]$$

$$\beta = \Phi^{-1}(\mathrm{P_F}) \qquad [3]$$

Typical values for β are back calibrated by Ellingwood et al (1980) and Milford (1988) at β_T = 3.0, with a typical value of 3.8 for Eurocode (EN 1990:2002). This corresponds to P_F values of 10^{-3} and 10^{-4} respectively over a design life of 50 years.

An advancement of reliability based design derived from experience with acceptable structural performance is to derive target reliability from the principles of risk optimization (JCSS-PMC 2001). This principle is now incorporated in international standardized practice (ISO DIS 2394:2013). Differentiated reliability levels are then derived as a function of the consequences of failure and the cost of structural performance. Risk based optimization is done in the cost domain. Separate procedures are applied in optimizing for life safety (Fischer et al 2013). A critical review of safety acceptance criteria in codes and standards is presented by Diamantidis (2008).

3.1. *Limit states design*

In reliability based limit states design, the overall structural performance is differentiated into separate limit states representing acceptable safety (ultimate limit state) and functionality (serviceability limit state) performance of the structure. The reliability function given by Equation [1] is then expressed in terms of a design function given by Equation [4] for each limit state.

$$R_d - E_d \geq 0 \qquad [4]$$

Values for R_d and E_d are assigned to achieve the target level of reliability for the relevant limit state. Safety compliance is required for each element of the structure; local damage to the structure is accepted under accidental conditions and robustness requirements are such that the overall integrity of the structure is not compromised by local failure.

The following differentiated reliability levels are used in standardized design (EN 1990:2002):

- Functionality of the facility, expressed typically as serviceability $\beta_{\mathrm{T,S}}$ = 1.5 for damage requiring repair;
- Safety levels further differentiated in terms of structural reliability classes, typically by increasing β_T by 0.5 to 1.0 for more important classes;
- Accidental design situations, which are not expected during the design life of the structure, typically with a 10% probability of occurrence; damage is accepted, but the reserve capacity of the structure is utilized to limit consequences to acceptable levels;
- Robustness, requiring damage due to unforeseen situations not to be disproportionate to the cause by ensuring the full reserve capacity of the structure is utilized.

3.2. *Extreme value modelling of environmental actions*

Probability models for the basic variables (R and E) of Equation [1] are required to derive the design values for Equation [4]. The Extreme Value Type I (Gumbel) distribution is representative of models used to derive characteristic values (50 year return period) and design values of environmental extreme conditions. Equation [5] provides the exceedance probability $F(x)$ of an occurrence (x) in terms of the mode (x_{mod}) and dispersion (α) parameters, as related to the mean (μ) and standard deviation (σ) of the annual extreme value.

$$\begin{gathered} F(x) = \mathrm{EXP}\big(-\mathrm{EXP}(-y)\big) \\ y = (x - x_{\mathrm{mod}})/\alpha \end{gathered} \qquad [5]$$

$$\alpha = \sigma\sqrt{6}/\pi; \quad x_{\text{mod}} = \mu - 0.577\alpha$$

The design value X_d for the extreme value X represented by Equation [5] can be derived in terms of the coefficient of variation ($v = \sigma/\mu$) and the probability of exceedance for the action, which is related to the target reliability level (β_T) through the sensitivity factor α_E (typically taken as 0.7; for accidental situations dominated by the extreme load the value of 1 may be appropriate), as given by *Equation* [6]. This expression can be used to determine a load factor (γ_E) to obtain the design load from the mean value as shown be Equation [7].

$$X_d = \mu\{1 - 0.45\, v - 0.78\, v \ln[-\ln[\Phi(\alpha_E \beta_T)]]\} \qquad [6]$$

$$X_d = \gamma_E \mu \qquad [7]$$

It should be noted that reliability based limit states design as outlined here is set up to ensure local resistance of the structure to loading from extreme environmental conditions and other sources. This is deemed to ensure acceptable global performance, based on a number of related considerations and measures.

3.3. *Design sensitivity to extreme value model parameters*

Environmental loads are sensitive to differences in the parameters of the extreme value models, for example when conditions for different regions are compared, or future changes of climatic conditions. Changes in the mean value can be associated with the intensity of extreme conditions; with dispersion related to the variability of such occurrences.

It should be noted that the relationship with climatic phenomena and the associated loading is not necessarily linear – it is indeed the case for precipitation, but wind loads are proportional to V^2 (V = wind speed) and wave loads to H^3 (H = wave height).

In a parametric sensitivity study of changes in the wind speed distribution parameters over a wide range of conditions for South Africa, changes in the load factor γ_E (Equation [7]) were found to be relatively insensitive to the original distribution parameters. The increase in γ_E by a factor M due to 5% changes in the mean or/and dispersion values for a typical Gumbel distribution is shown in Figure 1 for wind speed as a function of the target level of reliability for loading $\alpha_E \beta_T$.

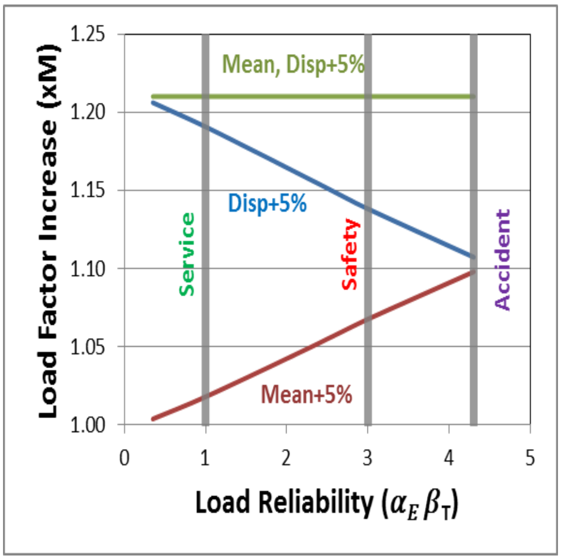

Figure 1. Sensitivity of strong wind load to changes in wind speed distribution parameters.

Generally wind loads are more sensitive to changes in dispersion than to the mean extreme value. Both parameters show a sensitivity for $\alpha_E \beta_T$, but with opposite trends. For changes in the value of the dispersion parameter, the corresponding increase in the design value of the extreme value load, is about four times; decreasing to twice the change at the upper end of typical values for $\alpha_E \beta_T$ corresponding to the situation where safety design is dominated by extreme wind loading. Changes in the mean value have little effect at the service level of reliability, increasing to double the increase in loading at the upper range of $\alpha_E \beta_T$. The combined effect of changes in both the mean and dispersion parameter values is an increase in strong wind load which is insensitive to $\alpha_E \beta_T$. Doubling of the combined effect can be related directly to the fact that the load is proportional to V^2.

4. RISK BASED DESIGN

As indicated or at least implied above, methodologies of risk are imbedded in the reliability procedures, where concepts such as the consequences of different levels of failure provide the basis for limit states design; or the classification of structures into reliability classes similarly reflect adjustment of performance levels for more important structures, where the consequences of failure are more severe.

The initial conceptual application of risk concepts in structural design is gradually being replaced by quantitative procedures, leading up to the application of risk optimization. Generic risk based procedures are used to derive rational values for β_T (ISO DIS 2394:2013) and for the basis of design of critical or complex facilities (ISO 13824:2009; JCSS 2008).

The nature of a risk based approach is illustrated by providing an outline of risk acceptance criteria and the application of risk concepts in performance based design procedures.

4.1. *Risk acceptance criteria*

The main characteristics of risk acceptance criteria, as shown in Figure 2, are constant risk limits across the consequence and probability domain and dual upper and lower limits, with the intermediate “as low as reasonably possible” (ALARP) region to be determined by risk optimization (ISO DIS 2394:2013). This scheme is conceptually consistent with present practice. Separate optimization procedures are applied for cost optimization and life safety.

4.2. *Risk acceptance at a global level*

It is important to consider the whole structure or system such as dam, port structure or bridge subjected to an extreme environmental hazard for example a storm or flood. From the optimization point of view it is useful to classify structures according to the possible consequences of collapse (i.e. global failure or failure of the main part of the structure).

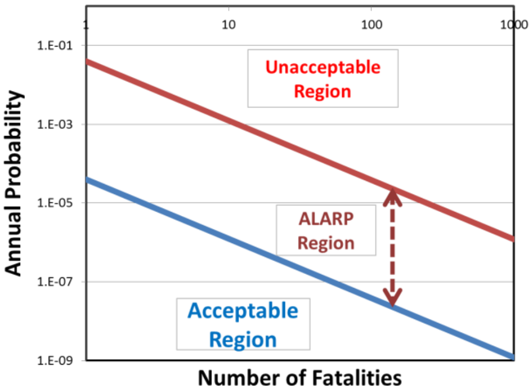

Figure 2. Illustrative risk criteria with ALARP transition between acceptable and unacceptable risk.

The consequences include human, environmental and economic consequences. In many cases three consequence classes are proposed (for further information on the topic see for example Canisius, 2011):

- CC3: high consequences
- CC2: medium consequences
- CC1 low consequences

Risk acceptance can be implemented in a simplified way through the performance objectives which specify the acceptable or tolerable response of the structure to the extreme environmental hazard scenarios. They should be defined on a global level, that is, as acceptable extent of collapse of the whole system or of its main part for a hazard with a specified intensity (event size) and an associated return period.

Table 1 illustrates an example for a possible performance matrix in terms of acceptable degree of damage for the three consequence classes and includes consequently the potential acceptable degree of damage of CC3 structures. Such a matrix forms the basis of performance-based design, for which global performance objectives are formulated. Local performance criteria can alternatively be used and substitute the aforementioned criteria for achieving global objectives.

5. INCORPORATION OF CLIMATE CHANGE IN EXTREME VALUE ENVIRONMENTAL ACTIONS

Present risk and reliability based design practice, as outlined above, serves as reference to establish the information required from climate change modeling and projections.

Table 1. Performance analysis: Acceptable degree of potential damage

Event size	CC1	CC2	CC3
Very large	Severe	High	Moderate
Large	High	Moderate	Mild
Medium	Moderate	Mild	Mild
Small	Mild	Mild	Mild

A summary of matters to consider are:

- It is clear that extreme value models are needed to be able to derive design values at various reliability performance levels.
- The direct manner in which climate change modelling and predictions can be presented in order to be used to adjust design parameters is to express changes in the intensity and rate of occurrence of extreme conditions in terms of mean and dispersion parameters of extreme value distributions.
- The first challenge is the ability to predict changes in rare extreme conditions with low probabilities of occurrence; including the rate of change within a time frame of several decades.
- Closer to the present situation is to improve the resolution of extreme conditions even before the effects of climate change are taken into account; serving as the basis for subsequent adjustment.
- However, until quantitative modelling of extreme climatic conditions and changes from historical conditions can be achieved, qualitative predictions can already be taken into account; close cooperation between climatologists and engineers will be required to implement such predictions in terms of design procedures.
- From Figure 1 it appears that design provisions for operational conditions i.e. serviceability level, expressed as reliability index values up to 1.5, is more sensitive for changes in the dispersion of extreme value models; at the safety level changes in the mean value of the extreme condition becomes more important, whilst the contribution of dispersion decreases, though it still dominates.

In practical terms the extreme value load is dependent on the climate phenomenon, for example with a linear relationship between temperature or snow precipitation, but non-linear relations for extreme wind or floods.

6. DISCUSSION AND CONCLUSIONS

From the limited survey of the potential impact of climate change on structural design:

1. Clear evidence of effects can be observed from conditions in Germany & South Africa.
2. Extreme climatic conditions and the impact of climate change have a direct bearing on economic infrastructure performance and design.
3. Structural design procedures based on principles of reliability & risk provide a proper basis for considering the effects of climate change.
4. Quantitative climate models on extreme conditions are needed as input to the adjustment of present design procedures.
5. Similarly the basis for representing structural performance needs to be significantly advanced in order to adjust to changes in extreme climatic conditions.

There is an acute need for close cooperation between climatologists and infrastructure designers in order to identify critical aspects of climate change related to extreme loads on infrastructure and to extract suitable information that could be used to serve as input to updating present design procedures.

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