# Reliability-Based Code Calibration in Civil Engineering: A Critical Review

M. Abubakar[1], J. I. Aguwa[2], M. Abdullahi[3] and S. Sadiku[4]

[1,2,3,4] Civil Engineering Department
Federal University of Technology, Minna
[1]Corresponding Author: mahmud1879@futminna.edu.ng

## Abstract

The use of new materials and the complexities in modern civil engineering infrastructures call for a systematic attempt to find accurate design solutions. It is clear that deterministic values are not reliable and that their use in the design of civil engineering structures can lead to instant failures. Thus, the use of the probability theory to determine the most reliable value of a parameter for the design of civil engineering structures is very relevant. This work is intended to review the literature on the application of probability theory in the calibration of civil engineering design codes. Consequently, to better evaluate designs and design details, it is important to understand the techniques as highlighted herein.

## Keywords

Code calibration, deterministic, probability of failure, reliability, uncertainty

### 1. Introduction

Structural design codes are essentially developed to provide a safe and economically efficient guide for the design and construction of ordinary structures under normal working load, operating and environmental conditions (JCSS, 2006). In this way, design codes not only promote the everyday work of structural engineers but also guarantee that a certain degree of standardization in the field of structural engineering is accomplished which eventually increases the effective usage of materials and resources.

Design codes typically form part of design algorithms, thus, making it possible to validate the safety of a specific design by merely comparing resistance and load effects. Since loads and resistances are subject to uncertainties, design values are incorporated in the design calculations to guarantee a proper degree of reliability for resistance and load effects. Design values of resistance and load are entered as the respective characteristic values divided by a partial safety factor (Mosley et al., 2007). Also, load combination factors are multiplied on one or more variable loads to take account of the variable load effects occurring concurrently.

Over the years, various methods have been used to determine design values for resistances and loads. From the permissible stress design to the Load and Resistance Factor Design (LRFD). Structural engineering as a field has an incredibly long history dating back to a few thousand years. During these years, knowledge has been collected to some degree through trial and error. The design of new types of structures or with different materials or subjected to new loading and environmental conditions had to be carried out based on conservative extrapolations of existing practise which mostly resulted in unsatisfactory results.

The method of structural reliability has also been gradually used over the past decades in the formulation of many pieces of testing and development of new design codes (Eurocode 0, 2001; NBR8681, 2003; SANS10160, 2011). The safety formats of the design codes can be selected using structural reliability methods in such a way that the degree of reliability of all structures designed following the same design code is standardised.

## 2. Concept of Structural Reliability

The ultimate goal of the structural reliability is to provide an answer to the question " how safe is safe? " taking into account the uncertainties inherent in the resistances and loads. Structural efficiency is measured using physical knowledge and scientific evidence-driven models. The models themselves and the parameters entering the models, such as material parameters and load characteristics, are unknown because of idealizations, the inherent uncertainty in the physical properties of materials and inadequate or insufficient details. The theory of structural reliability is based on the probabilistic modelling of these uncertainties and offers tools for quantifying the possibility that the structure will not meet the output criterion.

# 3. Basis of Reliability-Based Code Calibration

Design equations for checking the potential of various types of structural elements for different modes of failure are prescribed in code-based design formats like the Eurocodes. Thus, for the verification of a structural component, the standard format considering only dead and live loads is given in Equation 1 (Kohler and Fink, 2012)

$$G(.) = R_c / \gamma_m - \gamma_g g_c - \gamma_q q_c \tag{1}$$

where; $R_c$, $g_c$, $q_c$ are the characteristic values of the resistance, dead and live loads respectively, and $\gamma_m$, $\gamma_g$, $\gamma_q$ are the partial factors of safety for the resistance, dead and live loads respectively.

The resistance and load characteristic values are conventionally described by a certain fractal value of probability distribution of the random variable representing resistance and load. The recommended value for $R_c$ by the Joint Committee on Structural Protection (JCSS, 2001, 2006) is 5 per cent fractile of the lognormal distributed resistance, a 50% fractile (or average) of the normal distribution load constant at a time. $q_c$ is a 98% fractile of the annual maximum load variable distributable in time (JCSS, 2006). The corresponding partial safety factors can be calibrated based on the traditional range of $R_c$, $g_c$, $q_c$ to provide a design solution (z) with an appropriate likelihood of failure.

The probability of failure (Pf) is expressed as:

$$p_f = p_r\{g(X, R, G, Q) < 0\} \tag{2}$$

with

$$g(X, R, G, Q) = XR - G - Q = 0 \tag{3}$$

g(.) is the limit state equation, R, G and Q are resistance, dead and live loads respectively represented as random variables. X is the model uncertainty. The reliability of a structure is usually defined in term of reliability index, which is expressed as

$$\beta = -\Phi^{-1}(P_f) \tag{4}$$

Where $\Phi$ is the standard normal operator and $P_f$ is the probability of failure.

Generally, in terms of the various inputs of the permanent and variable load, different design circumstances are important. This can be considered with the following modification of Equations (1)

$$R_c / \gamma_m - \alpha\gamma_g g_c - (1-\alpha)\gamma_q q_c = 0 \tag{5}$$

alpha may take values between and including 0 and 1, representing different relative contributions of a permanent and variable load.

By solving the optimization problem in Equation 4, the partial safety factors for resistance, dead and live loads denoted by $\gamma_m$, $\gamma_g$, $\gamma_q$ can thus be calibrated:

$$Min\ f(\gamma_i) = \sum_{j-1}^{L} W(\omega_j, \beta_j(\gamma_i), \beta_t) \tag{6}$$

Given the increasing importance of the idea of reliability analysis, the present paper aims to provide a critical review of the procedures used in the calibration of the reliability-based code in Civil Engineering. The thematic problem consists of thirty-one (31) articles and is briefly outlined in the following paragraphs. The implemented methods in the following articles can be used in other civil engineering problems for further research.

The first paper entitled determination of safety factors for structural bamboo design applications by Sanchez et al., (2020). The authors of this paper noted that the use of bamboo as a building material has global potential as it is lightweight, highly sustainable and fast-growing. However, the pitfall is primarily due to the variability of the material properties identified by various researchers. Previous analysis has tried to associate particular material characteristics with environmental influences, but the findings are contradictory. Thus, the authors use the same methods historically applicable to other structural materials in the context of U.S. accepted criteria. They describe the importance of a common set of material properties to define the required safety factors that designers should implement when using bamboo to ensure a certain degree of durability and a reasonable rate of failure. Thus, their findings, when paired with international bamboo building codes, will lead to the greater structural use of bamboo in structural designs.

The second paper entitled Reliability-based partial factors for flood defences by Jongejan et al., (2020). The authors of this paper reported that the Netherlands has a system of main flood defences against large floods. However, these key flood defences have to meet requirements for flood safety. These are described in terms of overall allowed flooding probabilities as of 2017. The gap between part and system reliability is important for reliability assessments of flood defences. The code calibration method built to ensure compatibility between probabilistic and semi-probabilistic evaluations of flood control systems and their components is discussed in this article.

The third paper is a research report by Aguwa *et al*., (2019). The authors carried out a reliability-based calibration of modification factors for the Nigerian timber. The authors worked on seven different timber species commonly found in Nigeria. They carried out laboratory tests in accordance with BS 5268 to determine the bending and tensile stresses parallel to the grain and compression stress parallel and perpendicular to the grain and shear stress parallel to the grain. From the test results, statistical analysis was performed to obtain the statistical parameters associated with the timber species. The authors performed a reliability analysis of the timber species using CalREL software. In the reliability analysis, they considered five different failure modes. They went further to carry out sensitivity analysis for various failure modes. Modifications factors K1, K2, K3, K4, K7 and K8 were successfully calibrated and presented. The authors concluded by recommending the use of calibrated factors for the design of timber structures in the country.

The fourth paper entitled Load factors for earth retaining, reinforced concrete hydraulic structures based on a reliability index (β) derived from the Probability of Unsatisfactory Performance (PUP): phase 1 study by Ebeling. and White (2019). This scientific paper records the first of a two-phase research and development (RandD) analysis in support of the development of a hybrid technique of load and resistance factor design. Many of these reinforced concrete hydraulic systems are built on the soil and/or maintain it or are protected by an earthen element. Major soil-structure interaction is involved in the construction of each of these hydraulic systems. New numerical methods with adequate accuracy for a full LRFD study of these reinforced concrete hydraulic structures will enable reliability assessments given several limit states. The design of the structures requires up to six geotechnical and structural limit states and a seventh limit state relevant to performance. The authors of this paper arguably noted that the development of the required reliability procedures has been lagging in the geotechnical area as compared to those for structural limit state considerations and have therefore been the focus of this first-phase R and D effort.

The fifth paper entitled. Reliability-based calibration of partial factors for the design of temporary scaffold structures by Vereecken et al., (2019). The authors calibrated the partial factors for the design of temporary scaffold systems, based on reliability assessment. They stated that scaffolds are generally designed in compliance with the basic rules (e.g. EN12811, EN12810) and the details provided in codes of practise. There is no strong indication, however, that these design processes result in an acceptable and reliable level of safety for scaffold structures. Thus, acceptable target durability thresholds for facade scaffolds depending on which partial factors are calculated are proposed in the current report. The findings are based on simulations of various circumstances of scaffold design, taking into account samples produced by Latin Hypercube Sampling (LHS). The results of these simulations are processed by applying FORM analyses to the scaffold elements for buckling and yielding. In conclusion, annual indexes of reliability are found in the 2.5-3.5 range. This gives partial variables smaller than those found in existing design practices

The sixth paper entitled Calibrating partial factors - methodology, input data and case study of steel structures by Nadolski et al., (2019). The authors reported that partial factors are typically based on expert decisions and the calibration of previous design formats. Thus, for various types of building materials, loads and limit states, this ultimately results in unbalanced structural reliability. However, probabilistic calibration makes it possible to account for abundant structural performance requirements, environmental factors, level of production and quality, and so on. Taking into account the continuous updates of the Eurocodes and the creation of the National Annexes, the analysis offers an outline of the probabilistic calibration approach, provides input data for models of core variables and explains the implementation of the case study. The partial factors recommended in the current guidelines tend to provide for a lower degree of reliability than suggested in EN 1990. For the partial reasons for the applied loads, wind and snow, various values should be taken into consideration, appreciating the distinct existence of the uncertainties in their load impact.

The seventh paper entitled Reliability-Based Code Calibration for Load and Safety Factors for the Design of a Simply Supported Steel Beam by Barambu et al., (2017). In this research work, the reliability-based calibration of safety factors for the design of a simply supported steel beam, based on BS5950 (2000), was introduced. The design variables considered were modelled using CodeCAL program and the safety factors for the material, dead and live loads were calibrated by varying the safety index. From the results obtained, statistical prediction models were developed using the least square regression analysis for bending, shearing and deflection failure modes considered. The findings revealed that the safety factors for material, dead and live loads influenced by the safety index and it was also found that the safety factors for material, dead and live loads vary significantly for all failure modes. The authors, therefore, proposed that mathematical prediction models built in this study for bending and deflection failure modes should be used while designing a simply supported steel beam to BS 5950 (2000).

The eight paper by Aboshio *et al.,* (2016) titled reliability-based calibration of safety factors for the design of reinforced concrete staircase to BS 8110 (1997). The authors employed a reliability-based approach to calibrate partial factors of safety in BS 8110 for a typical reinforced concrete half-turn staircase design using CodCal: a Microsoft Excel-based reliability software developed by JCSS. They determined the statistical parameters representing the model uncertainty, resistance, dead and live loads and used the parameters in the software to determine the associated safety indices and probabilities of failure. Their results, however, showed that the design of reinforced concrete half-turn staircase to BS 8110 (1997) considering bending failure is to a great extent conservative and thus, the authors recommend that the resistance, dead and live load factors of safety be reviewed from the values of 1.15, 1.4 and 1.6 provided in the code to 1.02, 1.4 and 1.31 respectively.

The ninth paper by Tur and Nadolski (2016), entitled Belarusian national annexe to Eurocode 3: basic variables formulation for the partial factors calibration. Reliability studies based on various probability models will lead to incomparable outcomes. It is therefore important to establish common approaches to identify probabilistic models of basic variables. This paper explains the current approach to probabilistic modelling of action, with a focus on European trends. Probabilistic models of snow and wind loads, taking into account the territorial conditions of the Republic of Belarus, are explained. An analysis of the probabilistic models adopted for the calibration of the Eurocodes partial coefficients was carried out. Based on the investigation, a probabilistic model of action is proposed. Generalized data on the strength properties of steel, the geometric specifications of parts and the instability of the resistance models of steel components are provided based on an overview of recent science. The formulations of the basic variables were used to calibrate the partial factors for the Belarusian national annexe to Eurocode 3.

The tenth paper is titled “determination of new load and resistance factors for reinforced concrete structural members in Turkey” by Firat and Yucemen (2014). The authors carried out the implementation of the calibration procedure on a reinforced concrete beam subjected to permanent and variable loads considering shear failure. They assessed the statistical parameters for the quantification of uncertainty associated with design variables, modelling and loads and the resulting safety index determined based using the Advanced First Order Second Moment Method (AFORM). The result of the study, however, shows that the reliability index for the dead and live load combination (R=1.4G+1.6Q) for a reinforced concrete beam according to current practice and design criteria changes between 2.36 and 2.42 depending on design cases. The authors calculated the target reliability index for reinforced concrete beam subjected to shear mode of failure as 2.41. For new load and resistance parameters, the value of the target reliability index (βT) is taken as 3.0. As a result, new load and resistance factors were measured using the AFOSM approach and thus the design parameters of 0.80R > 1.20D+1.70L was proposed by the authors. The eleventh paper entitled lessons from the development of design standards in South Africa by Wium et al., (2014). Traditionally, most of the South African concrete design requirements have been based on British standards. However, with the implementation of the Eurocode by the United Kingdom, a reform of the South African building design codes started with the release of a loading code for buildings based on the Eurocode but tailored to the conditions and preferences of South Africa. An updated concrete code is an accepted version of the Eurocode, modified only in the National Appendix, whereas an adapted version of the Eurocode, supplemented by extracts from BS8007 is the standard for concrete water retention structures. In this paper, the authors offer a summary of the various methods and discussed crucial aspects of the revision of these standards.

The twelfth paper by Park *et al*., (2012) presented a reliability-based resistance factor calibration of driven steel pipe piles and the implementation of Load and Resistance Factor Design (LRFD) on practical design cases. The authors calibrated the resistance factors of driven steel pipe piles in the framework, based on reliability theory using static pile load test results. The results of fifty-seven load tests conducted to failure were compiled by the authors and were divided into three different groups based on the quality of the results. They performed reliability analyses for the three groups for two static bearing capacity equations and different target reliability indices (2.0 and 2.33 for group piles and 2.5 for single piles) following the First-Order Reliability Method (FORM) and using the Monte Carlo Simulation (MCS). They noted that the resistance factors were highly dependent on the quality of load test data. Thus, on an actual deign of bridge foundation, the authors applied the calibrated resistance factors. The case study findings showed that, in comparison with the Allowed Stress Design (ASD), using the resistance factors calibrated in their study, the evolved LRFD approach may lead to cost savings.

The thirteenth paper by Nowak and Rokoczy (2012) titled reliability-based calibration of design code for concrete structures. In this study, the authors developed a procedure for reliability-based calibration, statistical models for load and resistance. Reliability analysis for selected representative structural components and materials for selected target reliability indices was performed. The recommended resistance factors were thus selected. They collected test results for three groups of material: concrete, reinforcing steel bars and prestressing steel strands, from the industry. The authors observed, however, that the quality of materials has improved over the last 30 years which they say is reflected in the reduced coefficients of variation and increased bias factors as observed from the test results.

The fourteenth paper is titled target reliability for new, existing and historical structures presented by Nowak and Kaszynska (2011). The authors of this interesting paper stated that the target safety level depends primarily on two factors; failure implications and relative costs. They stated furthermore, that the target safety may also be motivated by social and political considerations in historical systems. In the authors' view, the current practice is an important guide and can thus be viewed as a verification of the design procedures. In terms of the safety index, they think, it is useful to calculate structural performance. Their paper reviewed the target reliability indices for beam and column designs in buildings and bridges based on ACI 318 and AASHTO LRFD design codes. They noted that there is a huge gap between new design standards and approval criteria for the appraisal of existing bridges. Also, owing to economic considerations, the target reliability index for current systems is lower.

The fifteenth paper titled reliability-based code calibration of partial factors of safety for Brazilian design codes presented by Beck and De Souza (2010). The research is based on actual data for wind load in South-East Brazil. Their investigation led to a set of optimized partial safety factors, which they compared to partial factors used in the Brazilian design codes. Results show that the optimized set of partial factors lead to more uniform reliability for different design situations and load combinations. The authors went further to assess the economic impact of replacing the set of partial factors provided in the Brazilian design code by the calibrated factors. Their findings also showed that it is possible to sustain the current level of reliability with the optimised set of partial safety factors and still produce an average 5 per cent reduction in expenditure on structural materials within the region.

The sixteenth paper is presented by Holicky *et al*., (2010), titled a study on the application of Eurocode EN 1992-1-1 in revising South African standard for structural concrete design SABS 0100-1, 1992. The authors considered partial safety considerations according to the specifications of the updated South African loading code SANS 10160. The result of their study shows that the partial factors $\gamma s = 1.10$ and $\gamma c = 1.40$ are a suitable set of factors for consideration in the proposed revision of the code. The authors concluded by recommending further research on model uncertainty for different structural members: flexural members, shear, columns, and walls, and the theoretical models of basic resistance variables related to quality control.

The seventeenth paper is titled Probabilistic modelling of timber structures written by Kohler et al.; (2007). The authors presented a proposal for the probabilistic modelling of the properties of timber material. Their proposed modelling which is within the framework of the Probabilistic Model Code (PMC) of the Joint Committee on Structural Safety (JCSS) is based on the discussions and feedback of COST E24 action participants and the JCSS stakeholders. The authors provided a summary of the basic reference properties for parameters of timber strength and ultimate limit state equations for timber components. For the basic properties, they presented the suggested probabilistic model and provided potential refinements regarding the update of the probabilistic model, given new details, modelling of the spatial variation of strength properties and the duration of load effects

The eighteenth paper entitled Reliability-based calibration of load duration factors for timber structures by Sorensen, et al., (2005). The authors observed that the load-carrying capability of timber structures decreases over time depending on the type of load and timber. Thus, they calibrated load duration variables, based on representative limit states and stochastic simulations for timber structures using probabilistic approaches. Also, the effects of the load duration are calculated based on a simulation of wind, snow and applied load realisations in compliance with the load models in the Danish Structural Codes. Three models of damage accumulation are identified, namely the Gerhards model, the model of Barrett and Foschi and the model of Foschi and Yao. Using data applicable to Danish structural timber, the parameters in these models are fitted with the Maximum Likelihood approach and statistical uncertainties are quantified. Reliability is assessed using representative short- and long-term limit states, and the kmod load length factor is calculated using the probabilistic model in such a way that short- and long-term configuration equations achieve equal reliability levels. The authors considered Time variant reliability aspect using a simple, representative limit state with time-variant strength and simulation of the whole lifetime load processes.

The nineteenth paper entitled Partial factors calibration based on reliability analyses for square footings on granular soils by Honjo and Amatya (2005). The authors determined partial factors of safety for square footings for highway bridges standing on granular soils using reliability-based analysis. Examples are selected based on a database providing extensive details on the shallow foundations of a highway bridge pier built-in 1869 in one fiscal year in Japan. The designs obtained, using formulas based on Meyerhof and Brinch Hansen's bearing capacity equations as updated by Vesic are compared. The complexities involved in the bearing capacity calculations are investigated by systematic literature analysis. The seismic forces calculated and fitted to a general Pareto distribution from the peaks over threshold analysis were taken into account. To calculate and compare the 100-year failure probabilities of the shallow foundations constructed, the first-order reliability system (FORM) and Monte Carlo simulations (MCS) are used. FORM is found to offer a significantly lower likelihood of failure than MCS.

The twentieth paper entitled Reliability-based calibration of Eurocodes considering a steel member by Gulvanessian and Holicky (2002). The authors stated that the major consideration of the methods of design suggested in EN 1990 is the reliability-based analysis of partial and load combination factors for different behaviours and material characteristics. Also, the steel structural member inquiry submitted focuses mainly on the implementation of the expressions (6.10) and twin expressions (6.10a) and (6.10b) of prEN 1990. The author added that partial factors need to be modified in all cases to achieve the necessary degree of reliability. Furthermore, the updated expression (6.10a) appears to offer an inappropriate solution for the countries of the two contributors, assuming lasting intervention only. To decide on the National Annex, further inquiries are appropriate.

The twenty-first paper entitled Calibration of Partial Safety Factors in Danish Structural Codes by Sorensen (2002). In his submission, the author stated that reliability-based code calibration is used to derive partial safety factors in the Danish structural codes and that the calibration is carried out in such a way that the calibrated partial safety factors result in the same average level of reliability as the previous codes, but with a much more uniform level of reliability. In the paper, the author explains the format of the code, the stochastic models and the resulting optimised partial safety factors. Also, he discussed the reliability level in relation to the code format and partial safety factors in the Eurocodes

The twenty-second paper by Vrouwenvelder (2002) presented a two-step reliability-based code calibration procedure. The author showed that in the first step, target reliabilities are set based on experience or optimization and in the second step, corresponding partial factors and other safety elements ( for example, PSI-values in Eurocode 1) are derived. The author concluded by illustrating the use of the JCSS Probabilistic Model Code in both steps of the two-step procedure and provided some illustrative examples based on the method of the standardised FORM coefficients and based to ISO 2394.

The twenty-third paper is titled Reliability-Based Code Calibration by Faber and Sorensen (2002). The authors introduced the basic principles of structural reliability theory and showed how the results of FORM-based reliability analysis may be related to the partial safety factors as well as the characteristic values. They further presented the code calibration problem in its principal decision theoretical form and explicitly discussed how acceptable levels of failure probability (or target reliabilities) may be established. The authors suggested values for acceptable annual failure probabilities for the ultimate and the serviceability limit states. The also described a procedure for the practical implementation of reliability-based code calibration of LRFD based design codes. The authors, in conclusion, discussed some important aspects relating to the difficulties encountered in practice when design codes are calibrated across a broad variety of types of structures, materials and loading conditions.

The thirty-fourth paper entitled Calibration of Reliability Elements for a Column by Markova (2002). The European Basic Document, EN 1990 Basis of Structural Design, requires national decisions to be made on alternative design procedures and the values of the different reliability elements. A basic example of a structural member made of different materials indicates that the combination of the three alternatives offered in EN 1990 contributes to inconsistent levels of reliability, which can further vary from those provided by the nationally adopted ENV 1991-1 pre-standard. The presented analysis of a column made of various materials reveals that to achieve a harmonised level of reliability, the partial factors for actions and material properties should be modified.

The twenty-fifth paper entitled structural behaviour and code calibration by Tanner (2002). The authors observed that the guidelines set out in the existing construction codes for composite bridges do not contain all applicable criteria for cross-section ductility representation. However, the built-in brittle behaviour cannot be omitted from the design of these systems. Using the basic concepts of the reliability theory applicable to composite bridges, the significance of structural behaviour for bridge reliability is studied by way of an example in this paper. Evaluation of bridge durability at device level shows that the likelihood of failure of the fracture structure significantly exceeds the probability of failure of the ductile behaviour of the same structure. The paper describes a realistic construction approach for composite bridges that makes it possible, on the one hand, to perform a separate study of the action effects and strength and, on the other hand, to ensure the ductile behaviour of the structures. Applying techniques of reliability, a procedure for the calibration of load and resistance models for the construction of ductile composite bridges is suggested.

The twenty-sixth paper is Calibration of Force Reduction Factors for RC Buildings presented by Mwafy and Elnashai (2002). The authors of this paper carried out a systematic research test and calibrate the force reduction factors (R) introduced in the current seismic codes. They used the refined expressions to measure the R supply factors for 12 buildings with diverse characteristics, covering a wide variety of medium-rise RC buildings. The "supply" values are then compared to the "design" and "demand" recommended in the literature. A wide list of Participant and Stage Reaction Parameters, including shear as a failure criterion, is used alongside a detailed modelling approach and a thoroughly validated analytical method. A systematic methodology is used to test R variables, including inelastic pushover and gradual structural collapse analyses using eight natural and artificial documents. In light of the details obtained from more than 1500 inelastic studies, it is concluded that it is important to incorporate shear and vertical motion in the estimation and measurement of R variables.

The twenty-seventh paper is titled Eighteenth Canadian Geotechnical Colloquium: Limit States Design for Foundations. Part II. Development for the National Building Code of Canada. In his paper, Becker (1997) outlines the work undertaken in the National Building Code of Canada on the original implementation of the LSD for Foundations. The author used an LFRD approach, based on the total geotechnical resistance factor. He derived the resistance factors for the ultimate limit states of bearing potential and the slipping for both shallow and deep foundations from the direct calibration of the working stress design (WSD) and reliability analysis. The author observed that the resistance variables obtained from both methods are reliable and have a relatively constant reliability index of roughly 3.0 to 3.5. He went further to present the relationship between the reliability index, the global factor of safety and resistance. He also presented examples of designs to prove that the proposed LSD produces designs that are similar to those created by the conventional WSD. He concluded by addressing the importance of serviceability limit states and also described the areas needing further analysis and testing to optimise code calibration.

The twenty-eighth paper entitled Structural reliability codes for probabilistic design - a debate paper based on elementary reliability and decision analysis concepts by Ditlevsen (1997). In this paper, the author argued that there is a substantial difference in the reliability level of any chosen probabilistic code format over the collection of structures specified by the partial safety factor code. There is a concern as to which of these thresholds to select as the goal level. The last issue must be acknowledged as the state of the art. It seems that it can only be addressed pragmatically by standardizing a particular code format. To get feedback on which of these various reliability levels in current experience to use as the target reliability standard, decision theoretical concepts are applied. The preferred probabilistic code format has a significant effect on the formal reliability metric. There is an immediate need, in the opinion of the author, to create a standard probabilistic reliability code.

The twenty-ninth paper entitled Calibration of partial safety factors by Arnbjerg-Nielsen et al., (1996). The authors, based on existing literature, presented an overview of the calibration of partial factors of safety and loads combination factors. They aim to recommend a standardized basis for calibration of partial factors of safety. Such calibrations were made to establish National Application Documents (NADs) and to determine partial safety factors and load combination factors in the Eurocodes/NADs. The paper includes a specific example formulated to illustrate the described method for code calibration.

The thirtieth paper entitled Development of geotechnical limit state design by Meyerhof (1995). The author investigated the historical developments of limit state design in Geotechnics. Comparisons are made with total and partial safety factors used for the design of land and offshore structures. The safety factors for the design of earthworks, earth retention structures and land-based and offshore foundations are found to be remarkably similar in various codes considering both ultimate and serviceability limit states. The uncertainty of loads and soil conditions, the specification approximations, and design tolerances are correlated with partial factors in the ultimate limit state design. They impact the nominal likelihood of the structure's failure and the magnitude of the failure that vary in land-based and offshore systems. The chances of fatality from typical encounters were contrasted with these odds. The author observed that the serviceability limit states are governed by structural and operational constraints and the intended service life of the land-based or offshore structure and that the corresponding partial factors are generally taken as unity.

The thirty-first paper is probability-based codified design: past accomplishments and future challenges by Ellingwood (1994). He stated that a basis for good engineering practise is provided by structural design codes and guidelines. Also, the method of designing probability-based codes has brought together the research group on structural stability and professional practise engineers and contributed to research against a shared objective that would not otherwise have been feasible. The author in his well-articulated paper, reviewed advances over the past two decades of probability-based codified structural design, evaluates the strengths and limitations of the latest generation of probability-based codes and proposes some avenues for new studies.

# 4. Discussion

Reliability-based-code calibration in civil engineering is concerned with the development of a new set of partial factors of safety for load and material and load combination factors in various civil engineering design codes using probability methods. This research area is important especially considering the arguments and concerns raised by the authors. As stated in the studies, the reliability method is, thus far, the best method to account for uncertainties inherent in design parameters. Additionally, due to the advancement in technology, it has become easier to obtain more accurate solutions for the complex problems whose solutions were oversimplified in the current design codes. A simple read-through shows that most of the papers have good introductions as several relevant studies were presented and the context of the studies shown. The problems addressed in the studies were clearly stated. It has also shown that even though tremendous achievements have been made in this area, the literature is still scanty, giving the importance of the research area in modern days coupled with the advancement in technology. The methods used to gather the data, on a general note, were clearly explained and the instruments and developments used were explained. Calibration procedures proposed or used even though a bit complex and could only be completed using developed computer programs, can be used for any structural material, loading, and environmental conditions. The best method is the implementation of the reliability approach using MCS. So far only one computer program is available for carrying out reliability-based calibration, thus there is an urgent need for same. Also, most of the papers considered values of parameters from the literature instead of experimental values. This no doubt will not give the desired result. The purpose of code calibration is to have factors for local use, however, many countries or regions are yet to start noticeable work towards having their localized factors, there is thus the need for every region to calibrate these factors for local use. For calibrated factors of safety to be generally acceptable, there is a need for multiple works by different researchers on the same factors in a particular region and the average or researches with similar results used as the acceptable factors. Lastly, the findings were well organized, sectioned, and reported objectively and conclusions were based on the findings and logically stated.

## 5. Conclusion

From the above, it is recognised that many evolutionary developments and breakthroughs have been made in the field of civil engineering in the last few years, especially concerning reliability-based code calibration for the design of civil engineering structures. This paper highlights quite recent historical insights on important contributions from the inception of reliability approaches to the field of reliability-based code calibration in civil engineering. The reason for the priority emphasis is that it is by far the most efficient way of working, in terms of minimising costs and maximising resources, thereby generating reliable systems. Therefore, the key skills needed are the ability to consider and predict the potential causes of failure, and knowledge of how to prevent them. To be able to evaluate designs and design details better, it is also important to know the techniques as highlighted in the previous sections.

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