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Reliability basis for assessment of existing building structures with reference to SANS 10160

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The principles of structural reliability are firmly established to provide the basis for structural performance as incorporated in design standards. Reliability-based procedures provide for variabilities and uncertainties that could reasonably be expected during the design service life of the structure. However, not all possible conditions to which all structures are exposed during such an extended service period can be accounted for effectively and economically at the design stage. The assessment of the reliability performance of an existing structure therefore forms an integral part of structural management and engineering practice. Despite the lag between the development and implementation of a basis for design and assessment of structures, the extensive body of information on structural assessment progresses steadily towards standardisation. This paper provides a review of the progress to provide background information towards extending the scope of South African structural standards to include guidance on structural assessment. The focus is on such developments to include provisions for existing structures in Eurocode, together with related investigations. In addition to a general review of background investigations, interrelationships between the basis of design and assessment for Eurocode (potentially also for South Africa) are considered. The main elements of a standardised basis for assessment are defined, and alternative assessment approaches are presented and demonstrated by representative examples. In conclusion, an outline of a possible development path for implementation in South Africa is provided.

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INTRODUCTION

Acceptance of the principles of structural reliability and risk is manifested by the introduction of the semi-probabilistic limit states approach, such as the partial factor or load and resistance factor methods, not only for South Africa, but also internationally by many countries and international organisations, such as ISO TC98, the Joint Committee for Structural Safety (JCSS) and the European Committee for Standardisation CEN TC250. Key concepts of the reliability-based approach are that structural performance is set in terms of target levels of reliability, with operational design procedures that are calibrated to exceed the target levels, whilst accounting for the diverse variabilities and uncertainties of all design or basic variables.

It is evidently not feasible to account, during the design stage, for all possible conditions to which the structure will be exposed during a service life of multiple decades. An extensive set of scenarios can be identified where conditions to which the structure is exposed, or even conditions of the structure as such, deviate from the design basis. Whilst the same principles of structural reliability on which the basis of design rests would apply to the reliability of the existing structure throughout its service life, the specific conditions requiring assessment of the structure provide a first indication that operational procedures for design and assessment are bound to differ. At the minimum level, the need for assessment of existing structures arises from the basic requirement for validating reliability compliance after decades of service. For structures designed to present standards, strategic upper bounds for assessment are required from needs such as life extension for economic reasons or sustainability objectives and future imperatives to account for climate change during the service life. Important classes of differences between design and assessment are the options for optimal decision-making under the respective conditions, including the state of information availability and gathering at the stage of decision-making.

Whilst the emphasis in structural engineering practice is rightfully placed on

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the design of new structures, the bulk of structures is in use, requiring some degree of structural management. Based on a growth rate of a few percent of the stock of structures over a 50-year service life, the ratio of existing-to-new structures is around 30, with 3 to 6 structures within their last 10 to 20 years of service life for each new structure being designed. Additional complications are early obsolescence or extended service life that will both have implications for the relative importance of the reliability performance of existing structures.

Professional duties regarding both public and economic interests should include the reliability of the collection of existing structures. A standardised approach towards reliability assessment has the potential for the most effective manner of dispensing with professional responsibilities, even if only the requirements for the basis of assessment are provided in a standardised format. The primary objective of this paper is to demonstrate that the principles of reliability and its conversion into operational requirements and procedures are sufficiently mature in standardised design to be converted also to the assessment of existing structures, in spite of the lag between development of these two modes of managing and decision-making on structural reliability.

Eurocode development of provisions for existing structures

This paper provides a review of recent developments for the introduction of the reliability basis for the assessment of existing structures in the format of standardised requirements, and alternative approaches and procedures. The survey includes background information that served as input to the development process, including historic progression of provisions for the closely related respective fields of design and assessment. The focus is primarily on the extension of the Eurocode Head Standard EN 1990 (EN 2002) to include assessment, as envisaged in prEN 1990 (EN 2020). The formulation of *Assessment and retrofitting of existing structures* (CEN/TS 17440 2020) and the accompanying *Background Documents* represent a key step in the development process. The CEN/TS is based on a number of national standards related to the assessment of existing structures, compiled in a Joint Research Centre report (JRC 2015). The paper provides an extension of the overview of recent developments provided by Holický *et al* (2019) and consideration of the applicability of these methodologies to South Africa by Retief *et al* (2019).

The International Standard ISO 13822 (ISO 2016a), first edition published in 2001, served as point of departure for the CEN Eurocode initiative. This standard, adopted as South African National Standard 13822 (ISO 2016a), represents the most direct provision for existing standards in this country. The specific case of the assessment of existing concrete structures is extensively developed in the *fib* Bulletin 80 (2016), with the proposed methodologies intended to be compatible with the Eurocode standardised approach, and with a view of extending the scope of a future edition of the *fib* Model Code for structural concrete. An extensive review of theoretical concepts for the probabilistic assessment of existing structures that could serve as basis for operational partial factor assessment methods is compiled by the Joint Committee on Structural Safety (JCSS 2001a), complementing the Probabilistic Model Code (JCSS 2001b); the latter arguably being biased towards the design process. These standardisation advances are based on an extensive body of literature and research, represented for example by the seminal papers by Allen (1991) and Ellingwood (1996), and more recent extensive investigations by Holický (2005), Vrouwenvelder and Scholten (2010), Tanner *et al* (2011), Steenbergen *et al* (2015), Sýkora *et al* (2017), and Holický (2017).

South African applications

The focus for the review and appraisal of this extensive body of information is provided by relevance to the Head Standard for the South African Loading Code SANS 10160-1 (SANS 2018) *Basis of structural design* which provides the requirements for the reliability performance of buildings and similar structural systems. The background to SANS 10160 is provided by Retief and Dunaiski (Eds) (2009), including the reliability principles (Retief & Dunaiski 2009), the relationship to Eurocode (Retief *et al* 2009) and an outline of the implementation of reliability principles in operational partial factor design in Eurocode by Holický *et al* (2009). The most significant differences of the South African standard compared to Eurocode are the limited scope of application, target reliability levels and resulting formats for action combinations, and the relationship between respective standards for actions and materials-based resistance. These differences need to be reflected when establishing the relationship between design of new structures and assessment of existing structures.

As a general guideline the conversion from the wide-ranging principles and procedures to the specific assessment procedures proposed for incorporation into SANS 10160 is intended to provide for standardised general practice; serving as a first round of assessment to identify the need for it and specifics of more refined investigations, assessment, decision-making and intervention. As a first step, procedures are directed towards complying with all the requirements that can be regarded as being equivalent to that for design, such as the relevant limit states and design situations, yet fully adapted to the existing structure under investigation.

The intention is that assessment procedures are limited to the semi-probabilistic approach, whilst requiring an appreciation of risk and reliability concepts to be able to adjust design parameters in accordance with information on the existing structure. Where the situation may arise that more advanced methods are justified, such as the application of full reliability-based assessment or risk-based and risk-optimised methods, the standardised approach should serve as initial investigation leading to specialist assessment using Eurocode procedures, whilst retaining consistency with South African requirements.

Since the condition of the existing structure related to its resistance generally plays a primary role in its load-bearing assessment, the scope of this review is simplified by mainly considering concrete structures, as opposed to the comprehensive Eurocode approach where all structural materials are included (in addition to all the structural classes of buildings, bridges and industrial and civil engineering structures). Even within the limited scope of this review, a substantial fraction of existing building structures will be covered. The investigation on existing concrete structures by the International Federation for Structural Concrete (*fib* Bulletin 80 2016) provides additional background information to complement this survey. Some indication is provided for extending assessment procedures to other structural materials, mainly considering steel.

ASSESSMENT PROCESSES AND PROCEDURES

Initial initiatives to formalise the assessment of existing structures emphasised the process of information gathering and decision-making, whilst quantitative methodologies were presented in general terms of the principles of reliability and risk. Flow charts of iterative processes of applying more detailed investigations and decision branches summarise the assessment process for both the JCSS (2001a) report and ISO 13822 (ISO 2016a). The requirements for a code for the assessment and format of its contents are provided by the JCSS report, whilst the ISO Standard provides a pro forma layout and specification. These documents represent key contributions to the advancement of standardised assessment. However, essential quantitative procedures are provided in theoretical and conceptual terms, lacking standardised procedures, such as approach and methodologies required to bring assessment on par with operational design standards.

The development of CEN/TS 17440 (abbreviated as CEN/TS) for the assessment of existing structures represents a significant advancement in closing the gap between standardised design and assessment. The presentation of a set of methodologies for the verification of the reliability of an existing structure forms an important part of this advancement. The verification methodologies are consistent with the relationship between the risk-based and reliability-based approaches for semi-probabilistic partial-factor methods specified by ISO 2394 (ISO 2016b). Since ISO 13822 (ISO 2016a) has served as starting point for the CEN/TS, the general format is also consistent with that International Standard. The implication is that the adaptation of the CEN/TS to South African standards will be consistent with the adopted International Standards SANS/ISO 2394 (ISO 2016b) and SANS/ISO 13822 (ISO 2016a).

Integration of the CEN/TS into prEN 1990 (EN 2020) should result in the final step of the advancement of standardised assessment. In accordance with the comprehensive nature of Eurocode, all classes and types of buildings and civil engineering infrastructure, bridges, industrial and geotechnical structures exposed to the inclusive range of actions covered by the standard are included in the scope of the CEN/TS.

The range of CEN/TS topics provides for the basis of assessment that is equivalent to the basis for design. The main topics include:

- The scope of conditions that may lead to the need for assessment of the structure
- Requirements and prerequisites in accordance with current standards
- The general framework for assessment to determine their actual conditions
- Methodologies for gathering information and updating of basic variables for the representation of actions and material properties
- Structural analysis for quantitative verification of structural elements and systems
- Alternative verification methods ranging from partial factors to risk assessment
- Construction and operational interventions
- Consideration of the special case of the assessment of heritage buildings.

Since quantitative reliability verification plays a central role in the assessment process and represents the most significant recent advancement, this paper focuses mainly on verification processes. Other topics are considered mainly from the perspective of their relationship to reliability verification.

Scope of situations requiring assessment

The scope of conditions and situations where the need for the reliability assessment of an existing structure arises can be related to the reliance of modern societies and economies on the built environment, where the structural or load-bearing behaviour of the facility forms an integral function. Trends in the continued use of structures, particularly for public buildings, but often in conjunction with economic constraints, require the application of advanced methods that may exceed the level of sophistication of design standards. The socio-economic differences between the design of new structures and the assessment of existing structures, as summarised in Table 1, provide an indication of the context to be applied to the respective requirements (Holický 2005).

More specifically, the nature and level of assessment of an existing structure are closely related to the need and motivation for such an assessment. Any situation where the condition of the structure deviates from the requirements and assumptions used by present structural standards may require an assessment to verify acceptable reliability and optimal performance. Such conditions may include exceedance of the design service life, outdated standards, deteriorating and obsolete materials, damage to the structure, the need for upgrading, refurbishing or life extension, and enhancing sustainability. In principle, possible critical situations for the structure should be identified in advance in the specification of the future performance of the structure in terms of utilisation and safety planning.

Various lists of circumstances leading to the initiation of assessment of the structure are provided as an indication of the scope of the document. These conditions should serve to determine the objectives, planning and methodology to be followed. The following list is based on the CEN-TS document, as elaborated on by Holický *et al* (2019) and extended by the JCSS (2001a) list, differentiating between circumstances that may have a bearing on how the assessment is to be done:

- Deviations from the original project description are observed
- Adverse results of a recent investigation or trends from periodic investigations
- Concern about the structural safety caused by evidence of damage
- Deterioration due to time-dependent environmental actions (e.g. corrosion, fatigue)
- Unusual incidents during use which could have damaged the structure (such as impact of vehicles, avalanches, fire, earthquake)
- Suspicion of possible impairment of the structural safety related to structural materials, construction methods or the structural system
- Discovery of design or construction errors
- Planned change of the use of the structure
- Changes in the structural system (e.g. retrofitting, modifications, extensions to the structure)
- A change of loads and loading conditions
- Extension of the design working life or expiry of residual service life granted from earlier assessment

Table 1 Differences between the design of new structures and the assessment of existing structures

Aspect	Design of new structures	Assessment of existing structures
Economic	Marginal costs of reliability improvements are usually low	Marginal costs of reliability improvements are usually high
Social	Restrictions are usually less significant than in existing structures	Restriction of the use and damage of economic and cultural assets are significant
Sustainability	New materials are often used, sustainability is difficult	Allowance for sustainability is enhanced substantially by using original materials

- Requirement of authorities, insurance companies or owners, or demanded by a maintenance plan
- Simply because of doubts about the safety of the structure.

The proper management of a structure throughout its service life could be added to the list, with the process starting as early as the commissioning of a new building.

More detailed specification of the assessment process can be formulated for classes of circumstances, such as a general class where the integral reliability needs consideration, concern about various classes of resistance impairment, and circumstances related to loading.

Reliability requirements

The central role of risk-based and reliability-based procedures for the design of new structures clearly also applies to the assessment of existing structures with the objective to verify acceptable levels of structural performance. Reliability requirements for assessment should therefore be consistent with those embedded in design procedures, both in terms of target levels of reliability, and in reliability differentiation between limit states and consequence classes for structures. Differences in reliability targets and classes in EN 1990 and SANS 10160-1 are therefore an important issue in adapting CEN/TS procedures for inclusion in the South African standard.

The comparison between design and assessment summarised in Table 1 provides a clear indication of the need for adapted reliability requirements for assessment. The derivation of appropriate reliability levels of existing structures is actively considered in the literature – see, for example, Vrouwenvelder and Scholten (2010), Steenbergen *et al* (2015), Holický *et al* (2015), Sýkora *et al* (2017), and Holický (2017). More elaborate reviews of the literature are captured by background investigations, such as JCSS (2001a), Lüchinger *et al* (2015), *fib* Bulletin 80 (2016). The relevant information from the literature is effectively embedded in the CEN/TS document but could serve as background input towards the extension of SANS 10160-1 to account explicitly for the assessment of existing structures.

In addition to the general motivation of refining the rational basis for determining reliability levels, the main issues related to assessment are safety costs, varying uncertainties, time-related reference periods and remaining service life.

Table 2 Definition of consequences classes

Consequences class		The more severe consequences of	
		loss of human life	economic
CC4	Highest consequences	Extreme	Huge
CC3	Higher consequences	High	Very great
CC2	Normal consequences	Medium	Considerable
CC1	Lower consequences	Low	Small
CC0	Lowest consequences	Very low	Insignificant

Reliability targets and classes

According to the Eurocode basic requirements, the selection of reliability levels by member states should be based on the following considerations:

- The possible consequences of failure in terms of risk to life, injury, potential economic losses
- The possible cause and/or mode of attaining a limit state
- Public aversion to failure
- The expense and procedures necessary to reduce the risk of failure.

Reliability levels which are related to the probability of structural failure are related to the consequences of failure, which are classified into five consequence classes (CC0 – CC4) that depend on societal and economic effects, as listed in Table 2. Eurocode provides for CC1 – CC3, considering the two extreme classes (CC0 and CC4) to be outside its scope. Indicative reference target reliability levels for the ultimate limit state are given in prEN 1990 (EN 2020), as listed in Table 3 for the one-year reliability index β_1 and failure probability P_f to be determined by member states. Procedures are based on CC2, typically with adjustments indicated for other consequence classes.

The values in Table 3 are based on previous studies and Annex C of prEN 1990 (EN 2020); seismic situations are excluded. It is not specified whether the values in Table 3 are applicable to accidental and fire design situations, and recommendations for Serviceability Limit States are absent.

The final draft of prEN 1990 (EN 2020) does not include possible transformation of the reliability level related to one year to levels related to other reference periods, even though this is needed to specify reliability elements for design and assessment of common structures.

Adjustment of reliability level

Transformation of target reliability index β related to different reference periods of n years is well known when the main uncertainty comes from actions that have statistically independent maxima in each year. Then the reliability (complementary to failure probabilities) $\Phi(\beta_n)$ related to the reference period of n years is determined from annual reliability $\Phi(\beta_1)$, where the index β_1 is related to one year, as the product of n annual reliabilities, thus on average as $[\Phi(\beta_1)]^n$. Consequently, the reliability index β_n can be assessed from β_1 using the expression indicated in the Eurocode EN 1990 (EN 2002):

Table 3 Indicative reliability levels related to one year and ultimate limit states given in prEN 1990 (EN 2020)

CC1	CC2	CC3
$P_f = 10^{-5}$	$P_f = 10^{-6}$	$P_f = 10^{-7}$
$\beta_1 = 4{,}2$	$\beta_1 = 4{,}7$	$\beta_1 = 5{,}2$

$$\Phi(\beta_n) = [\Phi(\beta_1)]^n \qquad (1)$$

Equation 1 indicates that, for mutually independent occurrences of failure in subsequent years, the commonly used reliability index $\beta_n = 3{,}8$ for $n = 50$ corresponds to $\beta_1 = 4{,}7$. However, the statistical maxima of actions (and other time-dependent variables) in subsequent years are usually correlated. Consequently, the occurrences of failures in subsequent years are inter-dependent. Then the relationship (Equation 1) should be generalised to take the correlation of failure events in subsequent years into account. A procedure for adjustment of reliability to different reference periods for correlated events is provided by Holický *et al* (2018).

Observations on target reliability

The following conclusions are related to the target reliability level:

- The target reliability levels recommended in various national and international documents are inconsistent in terms of the values and reference periods.
- In the latest draft prEN 1990 (EN 2020) of the revision of Eurocode EN 1990 the

target reliability level is indicated only for one-year and 50-year reference periods.

- Transformation formulae for adjustment of the reliability level to different reference periods, taking mutual dependence of failure probabilities in subsequent years into account, are missing.
- The proposed transformation formula for reliability index β_{nk} depends on the reference period n and independence interval k.
- Reliability index β_{nk} decreases with the reference period n and increases with the independence interval k.
- When determining the target reliability index, the assumption of annual independence of failures (k = 1) may be unsafe.

RELIABILITY VERIFICATION

Reliability verification of an existing structure shall be made using valid codes of practice, as a rule based on the limit state concept. Attention should be paid to both the ultimate and serviceability limit states. Verification may be carried out using partial safety factor or structural reliability methods with consideration of the structural system and ductility of components. The reliability assessment shall take the remaining working life of the structure into account, the reference period, and anticipated changes in the environment of the structure.

The conclusion from the assessment shall withstand a plausibility check. Discrepancies between the results of structural analysis (e.g. insufficient safety) and the real structural condition (e.g. no sign of distress or failure, satisfactory structural performance) must be explained. It should be kept in mind that many engineering models are conservative and cannot always be used directly to explain an actual situation.

The target reliability level used for verification can be taken as the level of reliability implied by the acceptance criteria provided in valid design codes. The target reliability level shall be stated together with clearly defined limit state functions and specific models of the basic variables. The target reliability level can also be established taking the required performance level for the structure into account, together with the reference period and possible failure consequences. In accordance with ISO 2394 (ISO 2016b), the performance requirements applied in the assessment of existing structures are the same as those used in the design of new structures. Lower reliability targets for existing structures may be used if they can be justified on the basis of economic, social and sustainable consideration (see Annex F to ISO 13822 (ISO 2016a)).

An adequate value of the reliability index β should generally be determined considering the appropriate reference period. For serviceability and fatigue the reference period equals the remaining working life, while for the ultimate limit states the reference period is in principle the same as the design working life specified for new structures (50 years for buildings).

Reliability of a structure is given by the condition $g(Xi) > 0$, where $g(Xi)$ denotes the limit state function and Xi represents the basic variables. Commonly the limit state function can be considered in a simplified form:

$$g(Xi) = R - E > 0 \qquad (2)$$

Here R denotes resistance while E denotes load effect. The reliability condition (Equation 2) can be verified by various methods.

The following procedures are included in the CEN/TS.

Partial factor method

When using the partial factor method, the reliability requirement (Equation 2) ($g(X_i) > 0$) is substituted by the condition:

$$g(x_{di}) = g(x_{d1}, x_{d2}, x_{d3}, ...) > 0,$$
$$x_{di} = x_{ki} \text{ or } x_{di} = x_{ki}\,\gamma(\beta) \text{ or}$$
$$x_{di} = x_{ki}/\gamma(\beta) \qquad (3)$$

Here x_{di} denotes the design values of basic variables X_i determined using their characteristic values x_{ki} and relevant partial factors $\gamma(\beta)$. The partial factors $\gamma(\beta)$ may be adjusted taking the specified reliability index β and actual characteristics of the basic variable into account (see *fib* Bulletin 80 (2016)).

Assessment value method

The condition (Equation 2) is modified by the requirement:

$$g(x_{di}) = g(x_{d1}, x_{d2}, x_{d3}, ...) > 0,$$
$$\Phi X_i(x_{di}) = \Phi(-\alpha_i\beta) \qquad (4)$$

Here αi denotes the FORM sensitivity factors and Φ the normal distribution function.

Probabilistic method

The requirement $g(X_i) > 0$ (Equation 2) is examined by the failure probability:

$$P_f = P\{g(X_i)<0\} < P_{f,t} \qquad (5)$$

Here Pf,t denotes the target probability of failure that is to be specified taking into account economic and societal consequences of failure, and the costs of improving structural reliability.

Risk assessment approach

The reliability is examined by acceptable risk expressed in a symbolic form as:

$$Risk = P_f C = P\{g(Xi) < 0\}C < Risk_t \qquad (6)$$

Here C generally represents any type of economic and societal consequences, and $Risk_t$ the relevant target risk level. Appropriate target risk level $Risk_t$ is to be specified individually, whilst accounting for the specific condition of an assessed structure. This may be a complicated task, particularly in the case of heritage buildings, where historical and artistic aspects are usually also involved. A general flowchart of the risk assessment procedure is shown in the CEN/TS Annex A. Principles of risk assessment may be used for cost optimisation procedures.

APPLICATION EXAMPLE

An existing building constructed in 1970 is to be renovated and a new assessment is required. The following example is limited to a simply supported reinforced concrete panel (a prefabricated hollow core floor panel) of a span L = 6 m. The panel should be exposed to additional permanent load due to a newly designed floor surface. The following requirements are specified: the remaining working life is 50 years, and the target reliability index related to the reference period of 50 years is β_t = 3,8. The target reliability can be adjusted to the actual economic and societal conditions. Table 4 indicates expected characteristic values of actions specified in accordance with valid standards, the load effect (the mid-span point bending moment) and the corresponding current capacity of the panel.

The load effect E and the resistance R of the panel are expressed as bending moments at the mid-span point of the panel. The characteristic values of the actions E_k and resistance R_k alone cannot be used to assess structural reliability; however, when $E_k < R_k$ this may indicate some safety margin.

The structural reliability of the considered concrete panel can be verified considering the limit state function (Equation 2) in a common form used for bending capacity of reinforced concrete cross section:

Table 4 Characteristic values of actions and resistance

	Permanent load G	Imposed load Q	Panel resistance R
Characteristic values	6.26 kN/m^2	1.50 kN/m^2	43.2 kN/m^2
Characteristic total actions	7.76 kN/m^2		–
Characteristic E_k and R_k	34.9 kNm		43.2 kNm

Table 5 Results of the applied assessment methods

Assessment method	Load effect (kNm)	Resistance (kNm)	Reliability index β	Results
Partial factors of Eurocodes	48.3 45.1	37.6	–	Negative
Adjusted partial factors	41.9	39.3	Assumed 3.8	Negative
Assessment values	40.3	41.0	Assumed 3.8	Positive
Probabilistic method	–	–	Assessed 4.2	Positive

$$g(Xi) = R - E = A_s f_y (d - A_s f_y /(2bf_c)) - (g+q)\, L^2/8 \tag{7}$$

Here A_s denotes reinforcement, f_y strength of reinforcement, f_c strength of concrete, d the effective depth and b the width of the panel cross section.

The application of the partial factors for design employing EN 1990 Equations (6.10) and (6.10a) respectively serves as reference for the assessment. A set of partial factors, which are adjusted for assessment, is applied to all the design variables for verification. Next, the probability models for the basic variables are adjusted and applied in accordance with the assessment value approach. Finally, a reliability assessment compares the reliability achieved to the target. The results of the panel assessment, including recommended decisions based on the applied verification methods, are indicated in Table 5. The consecutive steps demonstrate the effects respectively of reduced standardised assessment partial factors, assessment values accounting mainly for reduction in the coefficient of variation for the basic variables, and the reliability analysis to obtain the most likely limit state.

It follows from Table 5 that the partial-factor methods lead to negative results when both the partial factors recommended in Eurocodes and the adjusted partial factors obtained considering the index β = 3,8 are applied. The assessment value method (when index β = 3,8 is assumed to determine the assessment values) leads to a positive result. The probabilistic method also indicates a positive result, as the resulting reliability index β = 4,2 is greater than the required reliability level corresponding to the index β = 3,8. Therefore, for the remaining working life of 50 years the considered panel seems to be sufficiently reliable.

Cost optimisation procedures may be particularly effective when the reliability of a minor structure is acceptable (as in the case of the assessed floor panel); however, to increase the current reliability level for the required remaining working life, possible structural or operational interventions are considered. Then the procedure for the cost optimisation indicated below may be useful. In such a case the total cost $C_{tot}(x)$ including possible structural or operational interventions may be considered in the fundamental form (indicated in COMREL):

$$C_{tot}(x) = C_0 + C_1 x + C_f P_f(x) \tag{8}$$

Here $x = R/R_0$ denotes the intervention parameter (material consumption) to increase the present resistance R_0 to a desired level R, C_0 denotes necessary costs of intervention independent of the parameter x, C_1 denotes marginal costs per unit of the parameter x, C_f denotes costs due to failure and malfunctioning, and $P_f(x)$ denotes the probability of failure and malfunctioning. Figure 1 (obtained using the software product COMREL) indicates variation of the total costs $C_{tot}(x)$ with the parameter x, for selected relative costs C_0 = 0, C_1 = 10, C_f = 1 000 000 and structural failure $P_f(x)$ of the panel having the resistance $x\, R_0$.

Figure 1 indicates that the optimum increase of the resistance R seems to be 10 percent ($R/R_0 \approx$ 1,10). However, the

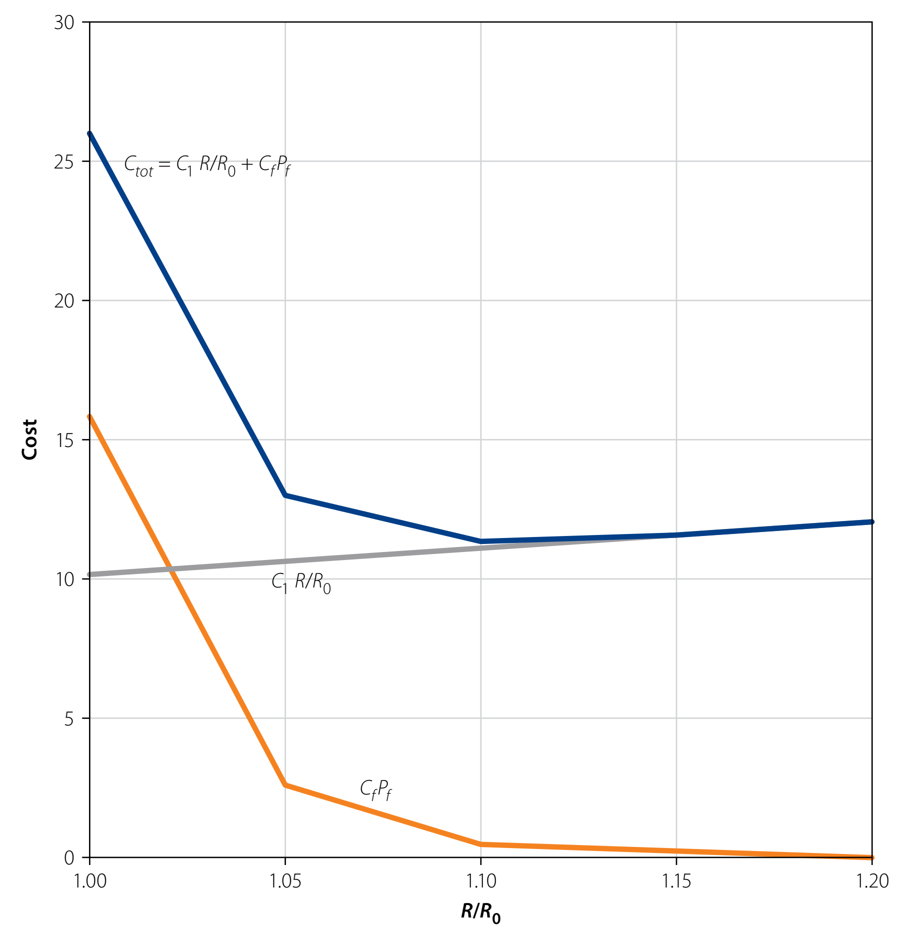

Figure 1 Variation of the total costs C_{tot} with the resistance increase R/R_0

convincing result should be based on appropriate failure cost C_f and marginal costs C_1.

This simple illustrative example of a floor panel may provide guidance to the assessment of a one-off structure, for example of a column or bridge element. It should be emphasised that the actual conditions and available data concerning action and resistance variables should always be accounted for. When only limited data is available, then advanced statistical methods (including data updating) can provide valuable techniques. In general, the relevant target reliability level (index β) and sensitivity factors α_E and α_R should be re-examined. In some significant cases the risk assessment method indicated in the CEN-TS may be advisable. When possible structural or operational interventions are considered (to increase the current reliability level even when it seems to be acceptable), then the cost optimisation of possible interventions may be applied.

Summary of Eurocode assessment approach

Advanced methods of structural risk and reliability are required to account for the extended scope of the basis for the assessment, in comparison to established procedures for the design of new structures. The set of assessment procedures presented here can be used to account for increasing levels of refinement associated with more demanding conditions or reliability classes. The partial factor method allows for the direct adjustments to account for modified reliability targets and uncertainty. The design value, probability and risk methods allow for increasingly taking benefit of the embedded conservatism of the approximations of the semi-probabilistic approach. More generally, the advanced reliability and risk-based methodologies are not only suitable for the assessment of existing structures, but also demonstrate the underlying depth of the basis of design of EN 1990 / prEN 1990.

The main principles of the upcoming European document on assessment of existing structures and building stock can be summarised as follows:

- Currently valid codes for the verification of structural reliability should be applied, while historic codes valid in the period when the structure was designed should be used as guidance documents.
- Actual characteristics of structural material, actions, geometric data and structural behaviour should be considered; the original design documentation, including drawings, should be used as guidance information only.

Table 6 Basic reliability elements for the ultimate limit state

Reliability element		Reliability class	
		RC2	RC3
Ultimate LS β_T (50-year)		3.0	3.5
Permanent load γ_G		1.2	$\times K_F = 1.1$
Variable load γ_Q		1.6	
Concrete composite	Reinforcement γ_s	1.15	Quality adjustment
	Concrete γ_c	1.5	

Table 7 Underlying probability models for basic variables

Basic variable		Distribution	Basic function $f(\beta)$	Mean	V_X
Permanent load G		Normal	$1 + \alpha_E \beta_T V_G$	1.05	0.10
Variable load Q	Imposed	Gumbel	$1 - V_Q\,(0.45 + 0.78\mathrm{LN}(-\mathrm{LN}(\Phi(-\alpha_E \beta_T)))$	0.96	0.24
	Wind			0.7	0.5
Resistance	Reinforcement	Lognormal	$\mathrm{EXP}(\alpha_R \beta_T V_R)$	1.0	0.10
	Concrete				0.15

STANDARDISED ASSESSMENT FOR SANS 10160-1

Justification for the incorporation of assessment procedures arises from the scope definition that *SANS 10160 is also applicable for the structural appraisal of existing structures*, but without providing any further guidance on the basis for such an appraisal. This implies rather strict and arguably unreasonable requirements and verification rules for these conditions. The challenge is to derive standardised procedures for assessment that are effectively equivalent to the requirements for the design of new structures, but with appropriate adaptation to conditions applying to existing structures. The equivalence requirement is not just an obligation, but has the advantages of a well-established reliability framework and built-in margins that can be exploited to counter many complications of assessment.

The three components of the conversion of the basis of design into assessment procedures are: (i) to identify the essential reliability elements that need to be adapted, (ii) to revert back to the reliability models on which they are based, and (iii) to modify the reliability elements in accordance with equivalent assessment requirements. An illustrative example is given here to indicate how reliability management can be employed to derive standardised partial factors for assessment.

The β-values for the reference reliability classes for the ultimate limit state and typical partial factors, as summarised in Table 6, are taken here to represent the standardised basis of design (SANS 10160-1). Partial factors are specified for the reference reliability class RC2, with adjustment for RC3 using the multiplicative factor (K_F). Partial factors for resistance are specified in the materials-based standards, represented here by the values for steel reinforcement and concrete as given by SANS 10100-1:2000 (SANS 2000), where no reliability differentiation is employed, but adjustment of quality control measures is recommended in the basis of design.

Notably this sparse set of information is sufficient to do design verification for an essential limit state, even allowing for reliability differentiation for an extensive range of building structures, such as residential and office buildings up to 4 and 15 storeys for reliability classes RC2 and RC3 respectively.

Reverse modelling of the partial factors listed in Table 6 can essentially be represented by the probability models for the basic variables as listed in Table 7, as extracted from background literature (Kemp *et al* 1987; Retief & Dunaiski 2009; Holický *et al* 2010; Botha *et al* 2018). The extensive body of reliability modelling that resulted in the provisions for the basis of design is deemed to be essentially

Table 8 Partial factors for design adjusted to assessment level

Application level	γ_G		γ_Q		γ_s		γ_c	
	RC2	RC3	RC2	RC3	RC2	RC3	RC2	RC3
Design	1.2	1.25	1.6	1.8	1.15	1.2	1.5	1.6
Assessment I	1.15	1.2	1.4	1.6	1.1	1.15	1.4	1.5
Assessment II	1.15	1.15	1.25	1.4	1.05	1.1	1.35	1.4

represented by these probability models through the standardisation decision-making process. All the essential features relating the partial factors to the reliability model are captured by these expressions.

The coarse resolution of the basis of design procedures are confirmed by the application of a single partial factor for variable actions γ_Q = 1.6 given in Table 6, despite the significant differences in the distribution parameters for the leading variable actions of imposed and wind load listed in Table 7. Structural resistance is represented by concrete as a composite material with V_X of 0.10 and 0.15 representing the control of resistance by steel reinforcement and concrete, respectively.

The final main step in adapting design procedures for assessment consists of the combination of the information from Tables 6 and 7, with parameter values adjusted to represent standardised assessment situations. The β-value is a key parameter in the process and will be used here as an example to demonstrate the process.

The reference β-values of 3.0 and 3.5 are based on calibration to existing practice for South Africa (Milford 1985; 1986). This range of values corresponds with the SANS/ISO 2394 value of 3.3 for normal buildings and medium cost of safety, adjusted from 1-year to 50-year reference periods according to Equation 1. Extensive optimisation by Fischer *et al* (2019) (their Figure 3) confirms that these values can be regarded as economically optimised (β_O). The potential for adjustment is indicated by the observation that β_O falls within the ALARP (as low as reasonably practical) range between the required societal upper limit (β_R) and the broadly acceptable lower limit. An indication of adjustment intervals is obtained from the reduction $\Delta\beta$ of 0.9 – 1.3 between normal and large cost-of-safety measures for the range of consequence classes considered in SANS/ISO 2394.

The effect of the adjustment of the β-values can be demonstrated in a sensitivity analysis at different assessment levels. A conservative value of $\Delta\beta$ = 0.5 is recommended by Diamantidis and Sýkora (2019) as assessment class I, and $\Delta\beta$ = 1.0 as assessment class II, based on the SANS/ISO 2394 classes of the cost of safety. Standardised sensitivity factors α_E and α_E of 0.7 and 0.8 are applied to action effects and resistance respectively. Since the γ-values listed in Table 7 incorporate provisions for model uncertainty (characteristic bias amongst others), they are adjusted in a normalised manner by the ratio $f(\beta - \Delta\beta) / f(\beta)$, where $f(\beta)$ represents the probability function listed in Table 7. The standardised partial factors for design are compared in Table 8 to the derived values for the two levels of assessment and the two reliability classes, rounded off to the customary values used in standards. The standardised partial factors are based on the coarse classification of safety costs and consequences and generic optimisation. It can be improved by proper risk optimisation when specific information is available by using the methodologies provided by the CEN/TS.

The adapted assessment partial factors provide a reasonable and apparently realistic set of values across the range of reliability and assessment classes, at least more nuanced than the K_F adjustment used for design. In principle, a more rigorous approach would reflect separate scaling of model uncertainty and characteristic bias as incorporated in the set of partial factors for design. However, the objective is primarily to illustrate equivalence of assessment with design, which is essentially achieved by the results given in Table 8.

Notable inconsistencies and approximations in the design provisions place a limit on the level of refinement for the derivation of assessment values. In addition to the approximate provisions for variable actions pointed out above, it should be noted that the SANS 10160-1 partial factors closely agree with (some) Eurocode values despite a $\Delta\beta$ = 3.8 – 3.0 between the two standards. Systematic background investigations for the formal introduction of provisions for the assessment of existing structures should explore the implications for all these and other issues on the conversion from design to assessment. The extensive Joint Research Centre (JRC 2015) survey on international practice should provide useful guidance on converting the CEN/TS procedures into operational rules for South African conditions.

CONCLUSIONS

The development of procedures for the assessment of existing structures that are based on the principles of risk and reliability still fits into the partial factor limit state approach for the design of new structures presented in this paper, and represents a significant advancement of structural engineering practice. These procedures form the basis for the CEN Technical Specifications for incorporation of the assessment of existing structures into the next version of the Eurocode Head Standard prEN 1990 (EN 2020). Due to the harmonised relationship of the South African Standard SANS 10160-1 to its Eurocode counterpart, this provides an opportunity also to introduce standardised assessment into this standard.

This paper demonstrates the series of progressively more advanced assessment methodologies that could be applied to obtain more refined verification results, based on the sequence of more rigorous reliability-based and risk-based analyses. An example is used to demonstrate the effectiveness of subsequent methodologies.

The introduction of provisions for the assessment of existing structures to South Africa is considered from the perspective of applying semi-probabilistic partial factor limit states procedures for building structures in accordance with SANS 10160-1 for use in general practice. The review provides an outline of the steps that need to be followed in the background investigations to arrive at appropriate procedures that could be standardised. Such a development would be similar to the adaptation of Eurocode standards to the South African Loading Code SANS 10160. A South African standard providing semi-probabilistic procedures that are consistent with the CEN/TS would make it possible, with specialist input, to also apply the reliability and risk-based approaches from the CEN/TS that are consistent with South African conditions. A similar policy is followed of limiting the scope of

SANS 10160 to normal design practice and allowing for the use of specialist Eurocode procedures where needed, rather than to adopt Eurocode standards comprehensively (Retief & Dunaiski 2009).

Two complementary perspectives are therefore presented in the paper, namely alternative methodologies for progressively advanced assessment analysis and verification for Eurocode, and a more operational semi-probabilistic approach that could be applied in standardised procedures. The mutual advantages would be the presentation of procedures that could be used extensively in normal practice, based on the advanced procedures that could be used by specialists where the stakes are high for assessment verification.

REFEFRENCES

Allen, D E 1991. Limit states criteria for structural evaluation of existing buildings. *Canadian Journal of Civil Engineering*, 18(6): 995–1004.

Botha, J, Retief, JV, Viljoen, C 2018. Reliability assessment of the South African wind load formulation. *Journal of the South African Institution of Civil Engineering,* 60(3): 30–40.

CEN/TS 17440 2020. Technical Specification. *Assessment and retrofitting of existing structures*. Brussels: European Committee for Standardisation.

Diamantidis, D & Sýkora, M 2019. *Reliability differentiation and uniform risk in standards: a critical review and a practical appraisal.* Paper presented at the Symposium on Future Trends in Civil Engineering, 17 October 2019, Zagreb, Croatia.

EN (European Standard) 2002. *EN 1990:2002. Eurocode – Basis of Structural Design*. Brussels: European Committee for Standardisation:

EN (European Standard) 2020. *prEN 1990:2002 (supersedes 1990:2002). Eurocode – Basis of Structural and Geotechnical Design*. Brussels: European Committee for Standardisation.

Ellingwood, B R 1996. Reliability-based condition assessment and LRFD for existing structures. *Structural Safety*, 18(2–3): 67–80.

fib Bulletin 80 2016. Partial factor methods for existing concrete structures. Lausanne, Switzerland: International Federation for Structural Concrete (fib).

Fischer, K, Viljoen, C, Köhler, J & Faber, M H 2019. Optimal and acceptable reliabilities for structural design. *Structural Safety*, 76: 149–161.

Holický, M 2005. Chapter 9: Assessment of existing structures. In Ellingwood, B R & Kanda, J (Eds). *Structural Safety and its Quality Assurance*. Reston, VA: American Society of Civil Engineers (ASCE).

Holický, M, Retief, J V & Dunaiski, P E 2009. The reliability basis of Eurocode. In Retief, J V & Dunaiski P E (Eds). *Background to SANS 10160.* Stellenbosch: SunMedia.

Holický, M, Retief, J V & Wium, J A 2010. Partial factors for selected reinforced concrete members: Background to the revision of SANS 10100-1. *Journal of the South African Institution of Civil Engineering,* 52(1): 36–44.

Holický, M, Diamantidis, D & Sýkora, M 2015. Determination of target safety for structures. *Proceedings,* 12th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP12), 12–15 July 2015, Vancouver, Canada.

Holický, M 2017. Operational approach to assessment of existing structures. *Proceedings,* 12th International Conference on Structural Safety & Reliability (ICOSSAR), 6–10 August 2017, Vienna, Austria.

Holický, M, Diamantidis, D & Sýkora, M 2018. Reliability levels related to different reference periods and consequence classes. *Beton- und Stahlbetonbau*, 113(1): 22–26.

Holický, M, Viljoen, C & Retief, J V 2019. Assessment of existing structures. In Zingoni, A (Ed). *Advances in Engineering Materials, Structures and Systems: Innovations, Mechanics and Applications.* Abingdon, UK: Taylor & Francis, pp 2109–2114.

ISO (International Organisation for Standardisation/ South African National Standard). 2016a. ISO 13822:2010/SANS 13822:2016. *Bases for Design of Structures. Assessment of Existing Structures.* Geneva, Switzerland: ISO.

ISO (International Organization for Standardisation/ South African National Standard). 2016b. ISO 2394:2015/SANS 2394:2016. *General Principles on Reliability for Structures.* Geneva, Switzerland: ISO.

JCSS (Joint Committee on Structural Safety) 2001a. Diamantidis D (Ed.) *Probabilistic assessment of existing structures*. Joint Committee on Structural Safety. SARL, France: RILEM Publications.

JCSS (Joint Committee on Structural Safety) 2001b. Joint Committee on Structural Safety. *Probabilistic Model Code*. **http://www.jcss.byg.dtk.dk**.

JRC (Joint Research Centre) 2015. Scientific and Policy Report, No 1247. *New European Technical Rules for the Assessment and Retrofitting of Existing Structures.* Luxembourg: JRC.

Kemp, A R, Milford, R V & Laurie, J A P 1987. Proposals for a comprehensive limit states formulation for South African structural codes. *Civil Engineer in South Africa*, 29(9): 351–360.

Lüchinger, P, Fischer, J, Chrysostomou, C *et al* 2015. *New European technical rules for the assessment and retrofitting of existing structures*. JRC Science and Policy Report. Luxembourg: Publications Office of the European Union.

Milford, R V 1985. *Calculation of a load index for ultimate limit state codes*. Report 85/6. Pretoria: CSIR National Building Research Institute.

Milford, R V 1986. *A guide for the calibrating SABS materials codes*. Report 86/16. Pretoria: CSIR National Building Research Institute.

Retief, J V & Dunaiski, P E (Eds) 2009. *Background to SANS 10160.* Stellenbosch: SunMedia.

Retief, J V, Dunaiski, P E 2009. *The Limit States Basis of Design for SANS 10160-1.* Stellenbosch: SunMedia.

Retief, J V, Dunaiski, P E & Holický, M 2009. *Review of Eurocode from the Perspective of the Revision of SANS 10160*. Stellenbosch: SunMedia.

Retief, J V, Viljoen, C & Holický, M 2019. *Standardized basis for assessment of existing structures.* In Zingoni, A (Ed) *Advances in Engineering Materials, Structures and Systems: Innovations, Mechanics and Applications.* Abingdon, UK: Taylor & Francis, pp 2120–2125.

SANS (South African National Standard) 2018. *SANS 10160-1:2010/2018. Basis of Structural Design and Actions for Buildings and Industrial Structures. Part 1: Basis of Structural Design.* Pretoria: SABS Standards Division.

SANS (South African National Standard) 2000. SANS 10100-1: 2000. *The Structural Use of Concrete, Part 1: Design.* Pretoria: SABS Standards Division.

Steenbergen, R, Sýkora, M, Diamantidis, D, Holický, M & Vrouwenvelder, T 2015. Economic and human safety reliability levels for existing structures. *Structural Concrete*, 16(3): 323–332.

Sýkora, M, Diamantidis, D, Holický, M & Jung, K 2017. Target reliability for existing structures considering economic and societal aspects. *Structure and Infrastructure Engineering*, 13(1): 181–194.

Tanner, P, Lara, C & Prieto, M 2011. Semi-probabilistic models for the assessment of existing concrete structures. *Proceedings,* 11th International Conference on Applications of Statistics and Probability in Civil Engineering, 1–4 August 2011, Zurich, Switzerland.

Vrouwenvelder, T & Scholten, N 2010. Assessment criteria for existing structures. *Structural Engineering International*, 20(1): 62–65.