Adaptation or Adoption of Eurocode Steel Design: A Comparison with South African Standard

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ABSTRACT: The globalization of world's economy combined with the information and communication revolution will, without doubt, impact the building and construction industry. For the South African construction industry to be competitive globally, the design engineer has to operate freely across the political and economic boundaries of the world. Contrary to the above, the South African Limit States Steel Design code for hot-rolled steel has not followed the route of European globalization and uniformity like the concrete design. The structural Eurocodes have managed to achieve convergence of a consistent structural design practice in Europe. The aim of this paper is to provide an overview of current developments in hot-rolled structural steel design. These include the formulation of the design principles and a comparison of the load factors, load combination and material resistance factors. The comparison of the material resistance factors is based on reliability indices performed using Monte Carlo simulation. Although the results of the comparison do not show significant differences, the design formulations in Eurocode are complex, and difficult to follow for a practicing engineer, thus making it difficult to adopt the Eurocode. However, in order to reduce technical barriers to international trade for South African practicing engineers, it is proposed in the paper to adapt the Eurocode with certain simplifications for the South African environment. The proposal includes the use of the material resistance factors calibrated against the current load factors recommended in the South African Loading Code. The Eurocodes, in any case, do allow for countries to use the National Application Document, through "boxed" values.

1 INTRODUCTION

Structural design practice varies substantially across the world; with different design loads, design methods, fabrication and construction techniques based on local tradition, performance of historical buildings and socio-economic circumstances. In Europe, the primary objective of establishing the structural Eurocodes was to achieve a consistent structural design practise throughout Europe, which would facilitate trade and encourage innovative designs. The standard that deals with the structural steel in Europe is EN 3 (2005), and the basis of design is covered in EN 0 (2002).

Historically, the South African concrete design standard was adopted from the British Standard BS 8110 (1985), and the steel standard SANS 10162-1 (2011) was adapted from the Canadian Standards Association (1994) with some minor modifications. Despite the concrete standard having now been adopted from the Eurocode concrete standard, the steel standard is still currently based on the Canadian Standard. The adaptation or adoption of the steel Eurocode is still unresolved, although there is some interest from South African practicing engineers as this may reduce the technical barriers to international trade, and improve their competitiveness. This is, however, despite the complex design formulations which are not familiar to the South African design engineer. In this paper, an attempt is made in comparing the South African loading standards (hereafter referred to as SANS 10160 (2018)) and the steel design standard (SANS 10162-1) to the corresponding Eurocodes, using structural reliability techniques.

SANS 10160 was developed and formulated based on the Eurocode EN 0 1990 (2005) and Eurocode EN 1 1991 (2005). A calibration was also undertaken by Ter Har and Retief (2001) to benchmark the load factors against the preceding South African loading code SABS 0160 (1989). In their calibration process, it was decided that the target reliability index of β_T=3.0 as stipulated in the predecessor standard SABS 0160 (1989) be left unchanged. EN 1 1991 (2005) on the other hand uses a reference reliability index value of β_T=3.8 and is therefore more conservative than the South African practice.

The South African steel design standard, SANS 10162-1 (2011), is based on the load and resistance factor design (LRFD) format. The LRFD format applies separate factors on the resistance and load effects to the design equations. The factors reflect the uncertainties in each parameter, and provides a balance between the reliability and cost of a structural design. However, the LRFD format provided in the loading code SANS 10160 (2018) is in terms of partial load factors and partial material factors and is given in the format

$$E_d < R_d \tag{1}$$

where E_d is the design value of the effect of actions and R_d is the design value of the corresponding resistance. E_d is determined as

$$E_d = E\,\{\Sigma\gamma_{F,i} \times \psi_i \times F_{k,i}\} \tag{2}$$

in which

$\gamma_{F,i}$ is the partial factor which allows for variability in action;

ψ_i is the combination factor accompanying the variable actions; and

$F_{k,i}$ is the characteristic value of action *i*.

The design value of the resistance R_d is defined as

$$R_d = \frac{1}{\gamma_R} \cdot R\left\{\Sigma \frac{x_{k,i}}{\gamma_m}\right\} \tag{3}$$

in which

γ_R is the partial factor covering uncertainty in resistance model and geometric deviations;

γ_m is the partial material factor for uncertainty in material property; and

$x_{k,i}$ is the characteristic value of material property, *i*.

The approach used to develop and calibrate the load factors in SANS 10160 is presented in more detail by Ter Haar and Retief (2001), and uses a concept of a Global Safety Factor (GSF) required to achieve a target level of reliability (β_T). The methodology essentially involves solving an inverse First Order Second Moment (FOSM) solution to obtain a target reliability of β_T = 3.0. The GSF is then obtained as a ratio of the mean values of resistance (μ_R) and total actions as

$$GSF_{mean} = \frac{\mu_R}{\mu_G + \mu_Q} \tag{4}$$

where (μ_G) and (μ_Q) are the mean values of permanent actions (G) and variable actions (Q) respectively.

The load combination scheme for multiple variable actions thus adopted in SANS 10160 (2018) based on this calibration and Turkstra's rule (Milford (1988)) is thus:

$$E_{d,STR} = 1.2G_k + 1.6Q_{k,1} + \textstyle\sum_{i>1} \psi_i 1.6Q_{k,i} \tag{5}$$

In situations where the dead load may become dominant, the standard further requires that the design should be checked for $E_{d,STR\text{-}P}$ where

$$E_{d,STR-P} = 1.35G_k + 1.0Q_k \tag{6}$$

The Eurocode EN 0 (1990) is based on the structural reliability principles as formulated in ISO 2394 (ISO 1998). The recommended design value method used in the calibration is based on semi-probabilistic approach. The design values are determined from

$$P(E > E_d) = \Phi(+\alpha_E\beta) \tag{7}$$

$$P(R \leq R_d) = \Phi(+\alpha_R\beta) \tag{8}$$

where β is the target reliability index, α_E and α_R are the values of the sensitivity factors. EN 1990 recommends α_E = -0.7 and α_R = 0.8. The values of β depend on the reliability class and the limit state. For example, for Reliability Class 2 (medium consequence for loss of human life and economic loss), ultimate limit state for 50 years, β_T=3.8.

Various combination schemes for actions are thus provided in the Eurocode for design actions of persistent and transient action in the format

$$Q_D = \textstyle\sum_{j>1} \gamma_{G,j} G_{k,j} \text{"}+\text{"} \gamma_P \text{"} + \text{"} \gamma_{Q,1} Q_{k,1} \text{"} + \text{"} \sum_{i>1} \gamma_{Qi} \psi_{0,1} Q_{k,i} \tag{9}$$

in which $\psi_{0,i}$ is a combination factor and the other symbols are similar to those defined in SANS 10160.

In this paper, SANS 10160 load combination schemes as presented by Equations (5) and (6) are reviewed using a Monte-Carlo simulation and compared to the load combination used in EN 0 (1990) as presented in Equation (9).

As highlighted earlier, the design of hot-rolled steel structures as provided in SANS 10162 (2011) is based on the Canadian Standard and uses the LRFD design format. The design capacity (R_d) is determined using the nominal capacity (R_n) and capacity reduction factor (ϕ) as

$$R_d = \phi R_n \tag{10}$$

A comparison of Equation (10) to Equation (3) shows that the partial material factors γ_m and partial resistance factor γ_R are combined in the steel standard to provide the capacity reduction factor ϕ (with $\gamma_R = 1.0$).

Despite the load factors having been calibrated against the predecessor SABS 0160 (1989) and the Eurocodes, the capacity reduction factors have, however, not been calibrated against the revised loading code SANS 10160 (2018). There is therefore a disjuncture between the loading code and the materials code SANS 10162-1 (2011). In addition to reviewing the load factors, this paper also reviews the calibration of the capacity reduction factors used in SANS and EN and compares the reliability of the structures designed using these standards. Based on this calibration, a recommendation for possible adoption or adaptation of the Eurocode is made.

2 CALIBRATION

2.1 *SANS AND EN Load Factors Calibration*

Section 1 reviewed the basic approach used in the calibration of load factors used in SANS 10160 (2018). In this section, an analysis of the load combination as provided in SANS and EN is made using Monte-Carlo simulation. The reliability performance function of the basic variables is given by

$$g(X) = R - Q \tag{11}$$

where R = resistance or load carrying capacity; and Q = maximum load effect that the member may be exposed to within its expected design and service life. The probability of member failure, P_f, is determined through the following convolution integral

$$P_f = \int_0^{\infty} F_R(q) \cdot f_Q(q) dq = \Phi(-\beta) \tag{12}$$

where $F_R(q)$ = cumulative distribution function of resistance and $f_Q(q)$ = probability density function of the load effect. Because of the advances, speed and memory capacity of computers, Monte-Carlo simulations are used to solve Equation (12) as

$$P_f \approx \frac{n(g(\boldsymbol{x_i}) \leq 0)}{N} \tag{13}$$

where $n(g(\boldsymbol{x_i}) \leq 0)$ denotes the number of trials n for which $g(\boldsymbol{x_i}) \leq 0$, and N is the total number of trials.

A Monte Carlo simulation was thus performed to determine P_f for parametric values of wind load ratios (α) and live load ratios (ξ) defined as

$$\propto = \frac{W_k}{G_k + Q_k + W_k} \tag{14}$$

and

$$\xi = \frac{Q_k}{G_k + Q_k} \tag{15}$$

The statistics of load effects assumed in this analysis are obtained from Kemp et. al. (1998) and Retief and Dunaiski (2009) and are presented in Table 2.

Table 2: Load Statistics

Variable Type of Load	Mean/Characteristic	Coefficient of Variation	Type of Distribution
Dead load (Permanent)	1.05	0.10	Normal
Live (office)[1] 'Lifetime max'	0.71	0.24	Gumbel Type I
Live (office)[2]	0.68	0.25	Gumbel Type I
Wind 'Lifetime max'	0.70	0.35	Gumbel Type I

[1] 5% characteristic [2] Point-in-time

The results of the Monte-Carlo simulation are given in Figures 1 and 2 for wind load ratio of $\alpha = 0$. Figure 3 presents a comparison of the results between SANS and EN for load combinations of $1.2G_k+1.6Q_k$ and $1.35G_k + 1.5Q_k$ respectively, for wind load ratio $\alpha = 0$. In all the graphs, the reliability index β is plotted as a function of the live load ratio. For $\alpha = 0$, the envelope reliability index is uniform for load combinations of dead (G_k) plus live load (Q_k); both for SANS 10160 and EN.

For hot-rolled steel, the live load ratio is between 0.5 and 0.8, and it is apparent from Figure 3 that β is close to 3.3 for SANS ($1.2G_k+1.6Q_k$) and β is between 3.0 and 3.5 for EN ($1.35G_k + 1.5Q_k$). For higher wind ratio ($\alpha = 0.6$), Figure 4 shows that β lies between 2.7 and 3.0 for SANS and EN has a uniform β value of 2.7. The target reliability index as required in SANS 10160 (2018) is $\beta_T = 3.0$, and is achieved except for low live load ratios. Furthermore, in Figure 1 (SANS), it is apparent that the $1.35G_k+1.0Q_k$ combination dominates for live load ratios less than approximately 0.2 (i.e. $Q_k<0.25G_k$). This observation is in line with what was observed by Ter and Retief (2001).

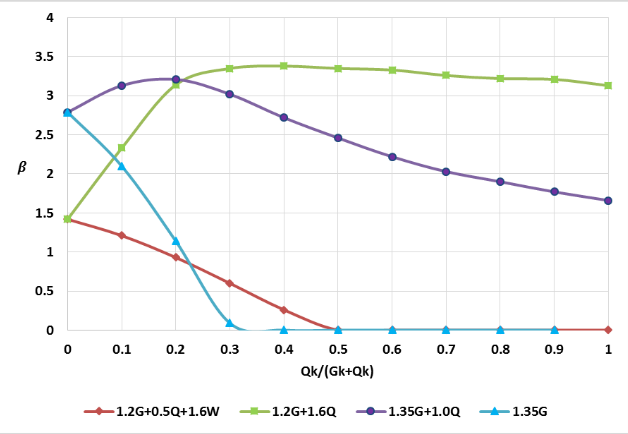

Figure 1. SANS 10160 (α = 0)

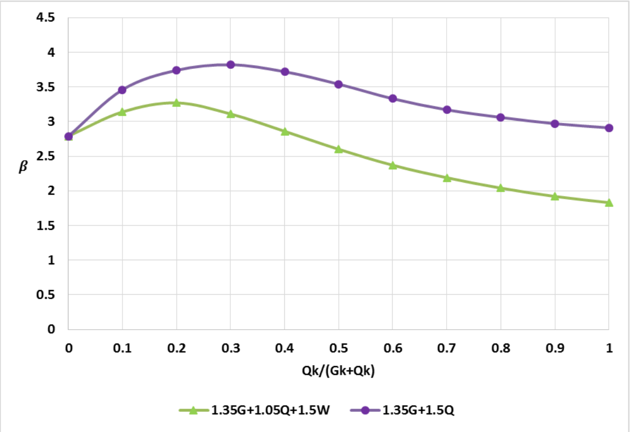

Figure 2. Eurocode (α = 0)

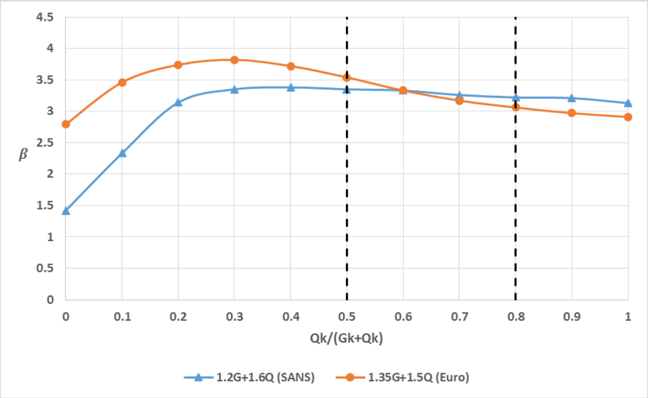

Figure 3. Comparison of reliability indices (α =0)

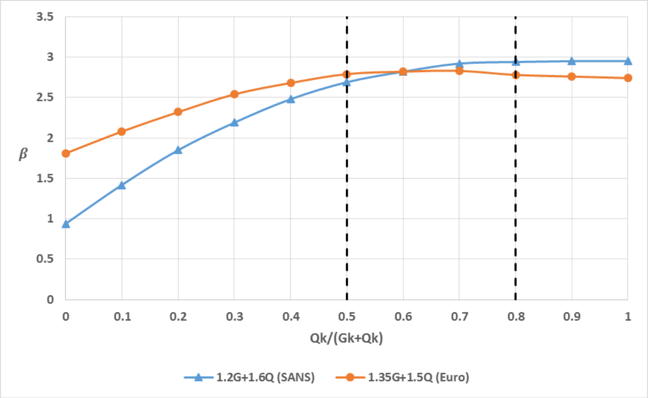

Figure 4. Comparison of reliability indices (α = 0.6)

2.2 *Materials Resistance Calibration*

In this paper, further calibration analysis will be presented for a hot-rolled steel member subject to bending. To illustrate the differences, if any, between SANS 10162-1 (2011) and EN 3 (2005), consideration will be made for the moment capacity of a compact class 1 section subject to uniaxial bending moments with continuous lateral supports. In SANS 10162-1 the moment capacity is given as

$$M_r = \emptyset Z_{pl} f_y \tag{16}$$

where;

Z_{pl} = plastic section modulus;
f_y = nominal member moment capacity; and
ϕ = capacity reduction factor ϕ= 0.9.

EN 3 provides a similar equation as

$$M_{c.Rd} = \frac{W_{pl} f_y}{\gamma_{Mo}} \tag{17}$$

where the resistance factor γ_{Mo} = 1.1.

A comparison of Equation (17) to (16) shows that

$$\phi \approx \frac{1}{\gamma_{Mo}} \tag{18}$$

For a given set of load factors and load combinations, the uniformity of the reliability index β depends upon, amongst other factors, the level of the target reliability index and the coefficient of variation of the resistance of the member.

A Monte Carlo simulation was performed for a member subject to bending. The first analysis was to consider the variation in β for various live load ratios, with the following three values of capacity reduction factors (i.e. ϕ = 0.95; 0.90; 0.85). The choice of the capacity reduction factors was to determine the influence and extent of the reliability compared to what is recommended in the standards; the value recommended in SANS being 0.9.

Due to limited availability of data, the probability distributions of the material resistance were assumed to be normal (NBS Special Publication (1980)), with

$$\frac{\bar{R}}{R_k} = 1.07 \quad and \; V_R = 0.13 \tag{17}$$

where $\bar{R}$ is the mean resistance, R_k characteristic resistance and V_R is the coefficient of variation. Future research would be required to validate these material statistics. The load factors and load combination factors used are those obtained from SANS and EN.

The results of this analysis are shown in Figures 5-8 for different load combinations and wind load ratios.

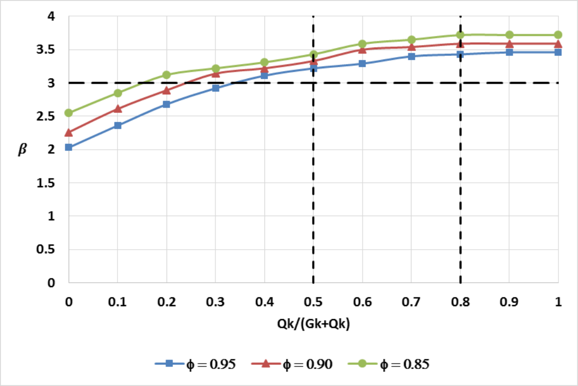

Figure 5. Variation of SANS reliability index with ϕ {For: $1.2G_k+1.6Q_k$, $\alpha = 0$}

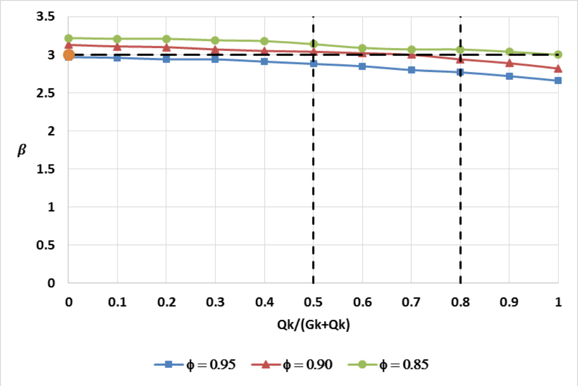

Figure 6. Variation of SANS reliability index with ϕ {For: $1.2G_k+0.5Q_k+1.6W_k$, $\alpha = 0.6$}

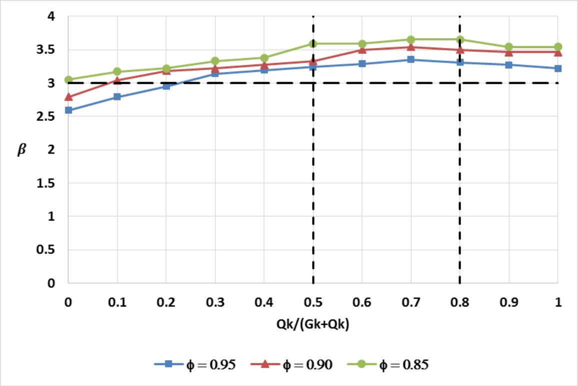

Figure 7. Variation of EN reliability index with ϕ {For: $1.35G_k+1.5Q_k$, $\alpha = 0$}

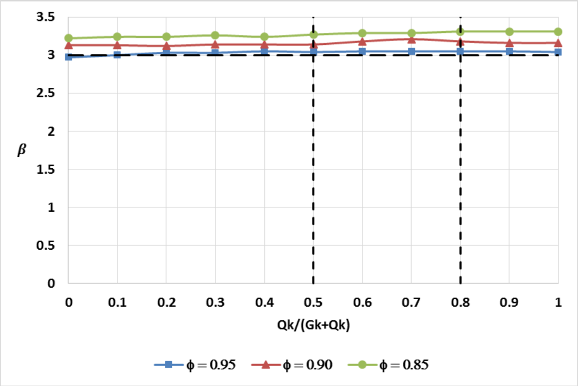

Figure 8. Variation of EN reliability index with ϕ {For: $1.35G_k+1.05Q_k+1.5W_k$, $\alpha = 0.6$}

3 ANALYSIS AND DISCUSSION OF RESULTS

From Figure 5, β is a constant for practical live load ratios between 0.5 and 0.8, and ranges fairly uniformly between 3.2 and 3.5 for $\phi = 0.90$ (SANS 10162). However, for lower live load ratios, β reduces to about 2.2, showing the dominancy of the dead load. From the same figure, β increases to about 3.7 for $\phi = 0.85$. Figure 6 presents the results for the load combination $1.2G_k+0.5Q_k+1.6W_k$ where it is shown that β becomes more uniform at 3.0 for all live load ratios and wind load ratio $\alpha = 0.6$, as recommended in the standard.

A similar analysis is presented in Figures 7 and 8 for the EN 3. The EN shows the β values to be uniform around 3.3 for the load case $1.35G_k+1.5Q_k$. For the load case of $D+L_{apt}+W_{max}$, where the wind load ratio is high ($\alpha = 0.6$) as shown in Figure 8, the reliability index is uniform for all live load ratios at $\beta = 3.1$. This provides a slightly lower probability of failure compared to SANS. The consistency in both standards is irrespective of the capacity reduction factors. A choice of $\phi = 0.85$ would therefore be more conservative in the practical ranges of the live load ratios.

A comparison of the two standards is presented in Figures 9 and 10, for the load combinations shown in the figures. It is thus clear from the figures, that the two standards provide the same order of magnitude of reliability in the live load ratios of practical interest between 0.5 and 0.8. For the load combination of Dead plus Live, SANS provide a higher probability of failure for low live load ratios, with the β value going to as low as $\beta = 2.2$. This may pose a problem to buildings with high consequence of failure.

On the contrary, EN 3 provides a much more uniform probability of failure for almost the whole range of live load ratios. However, the two standards provide a very close reliability for the practical live load ratios.

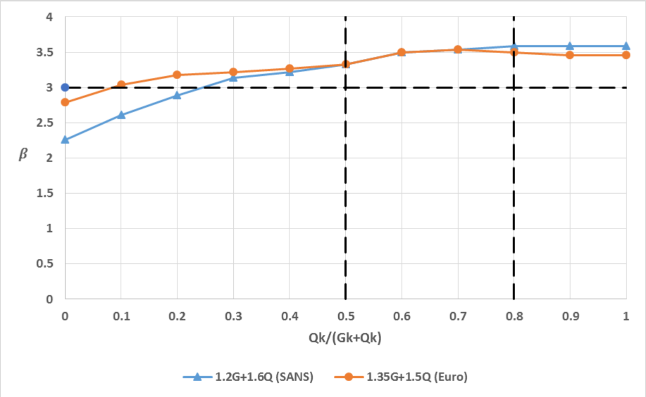

Figure 9. Comparison of β for $\alpha=0$ and $\phi=0.9$ (Dead + Live)

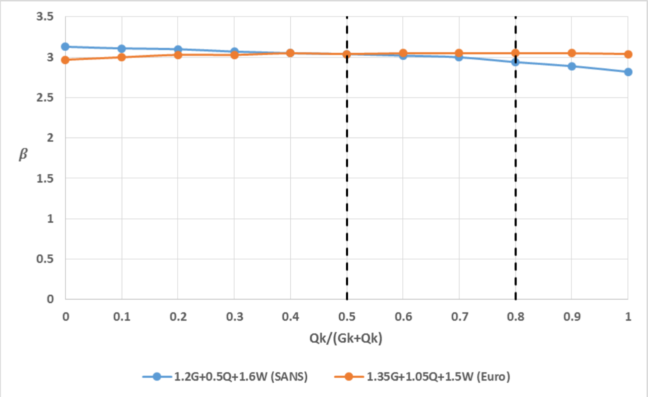

Figure 10. Comparison of β for α=0 and ϕ=0.9 (Dead + Live_{apt} + Wind_{max})

4 CONCLUSIONS

The paper has reviewed the calibration of the load factors and load combination as presented in SANS 10160 (2018) and EN 0 (1990). The load combination almost achieved the target reliability index of $\beta_T = 3.0$.

Based on the load combinations provided in the two standards, a Monte Carlo simulation was performed for a steel member section under bending. Material resistance statistics were assumed as normal. The results have shown that β is dependent on the capacity reduction factor, load combination and the live load ratio. For practical ranges of live load ratios, both standards exhibit uniform reliability in compliance with the target reliability index of 3.0.

This paper has therefore demonstrated that it is possible for South Africa to adapt the Eurocode EN 3 steel design, whilst retaining the current load factors and load combination factors as this will still produce the same performance of reliability. However, various calibrations may still be required for other member sections and connections and more research is required on material resistance statistics. An adoption of the Eurocode without any calibration will mean a complete acceptance of the code without due consideration of local environment and performance of currently as-built structures. Furthermore, the issue of the high volume, complex EN standard may need to be addressed, considering that the outcome of the two standards is the same. Perhaps certain sections which are not covered in SANS may need to be adopted from the EN Standard.

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