CALIBRATION OF PARTIAL RESISTANCE FACTORS FOR COLD-FORMED STEEL IN SOUTH AFRICA

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ABSTRACT

In 2011, the South African Loading Code (SANS 10160) was revised to align with international standards and benchmarked against the Eurocodes. The factors of safety were derived using a target level of reliability of (β = 3.0) as opposed to that used for the Eurocode (β=3.8). This target reliability was in line with the previous code provisions of SANS 10160 and ISO 2394. In this paper, a review of the load factors is made and it is shown that the current factors in the code produce a uniform level of reliability for different dead load ratios. The paper then looks at the development of the resistance factors for cold-formed steel for South Africa. The South African materials standard for cold-formed steel (SANS 10162-2) was adopted from the Australian-New Zealand (AS/NZS) standard and hence requires a calibration against the South African Loading Code. An investigation is made in the variation of the safety index with load ratio for different ratios of the mean resistance to the design resistance ($\bar{R}/R_d = \bar{R}/\emptyset R_n$) using the new load factors in SANS 10160. This is done for different dead, office live and wind loads for a given coefficient of variation. From the results, it is seen that the safety index is reasonably uniform with varying load ratio. For a given set of load factors and load combinations, the uniformity in the safety index will depend, amongst others, on the level of the target safety index and the coefficient of variation of the resistance member. The resistance factors φ for use in the cold-formed steel design are thus recommended.

Keywords: Cold-formed steel, material resistance, reliability index, SANS 10162

1. INTRODUCTION

Cold- formed steel elements are mainly used as structural members, floors, walls, diaphragms and roofs in building construction. The advantages in the use of cold-formed steel are well documented (Hancock [1]), with the main advantage being the light weight which results in reduced costs. In South Africa the design of cold-formed steel is covered in the national standard SANS 10162-2 [2]. This standard is based on limit state design and recommends that a design can be based on either effective width method or direct strength method.

However, loading requirements are covered in the South African National Standard SANS 10160 [3]. The loading standard was developed and formulated based on the Eurocode EN 1990 [4] and EN 1991 [5]. A calibration was also undertaken by Ter Har and Retief [6] to benchmark the load factors against the preceding South African loading code SABS 0160 [7]. In this calibration process, it was decided that the reliability index of β = 3.0 as stipulated in SABS 0160 [7] be left unchanged. EN 1991 [5] on the other hand uses a reference reliability index value of β = 3.8 and is therefore more conservative than the South African practice.

The South African cold-formed steel design standard, SANS 10162-2 [2], is based on the load and resistance factor design (LRFD) format, where load components are multiplied by load factors and resistance is multiplied by a resistance factor. However, the LRFD format provided in the loading code SANS 10160 [3] is in terms of partial load factors and partial material factors and is given in the format

$$E_d < R_d \qquad (1)$$

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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

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

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 methodology used to develop and calibrate the load factors in SANS 10160 [3] was that proposed by Ter Haar and Retief [6], which uses a concept of a Global Safety Factor (GSF) required to achieve a target level of reliability. The methodology essentially involves solving an inverse First Order Second Moment (FOSM) solution to obtain a target reliability of $\beta_T = 3.0$. 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 means of permanent actions (G) and variable actions (Q) respectively. The load combination scheme for multiple variable actions thus adopted in SANS 10160 [3] based on this calibration and Turkstra's rule (Milford [8]) is thus:

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

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

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

In this paper, the load combination schemes as presented by equations (5) and (6) are reviewed using a different approach to the GSF. Instead, a safety index approach is used as explained in the next section.

As highlighted earlier, the design of cold-formed steel structures is provided in SANS 10162-2 [2]. However, this standard is based on the Australian/New Zealand Standard AS/NZS4600 [9]. The design capacity (R_d) is determined using the nominal capacity (R_n) and capacity reduction factor (ϕ) as

$$R_d = \phi R_n \tag{7}$$

A comparison of equation (7) with equation (3) shows that the partial material factors γ_m and partial resistance factor γ_R are combined in the standard to provide the capacity reduction factor ϕ (with $\gamma_R = 1.0$). Table 1 presents some of the capacity reduction factors as recommended in SANS10162-2 [2].

Table 1: Capacity Reduction Factors

Design Capacity	Capacity Reduction Factor
Members subject to tension	$\phi_t = 0.90$
Members subject to bending • Section moment capacity • Member moment capacity	 $\phi_b = 0.95$ $\phi_b = 0.90$
Concentrically loaded compression members	$\phi_c = 0.85$
Butt welded connection in tension/compression	$\phi = 0.90$
Tear-out bolted connection	$\phi = 0.60$

It is therefore apparent that despite the load factors having been calibrated against the old SABS 0160 [7] and the Eurocodes, the capacity reduction factors have not been calibrated against the revised loading code SANS 10160 [3]. There is therefore a disjuncture between the loading code and the materials code SANS 10162-2 [2]. In addition to reviewing the load factors, this paper also reviews the calibration of the capacity reduction factors and makes recommendations for further research work.

2. CALIBRATION

2.1 Load Factors Calibration

Section 1 reviewed the basic approach used in the calibration of load factors used in SANS 10160 [3]. In this section, an analysis of the load combination as provided by equations (5) and (6) is made using the safety index approach. The reliability performance function of the basic variables is given by

$$g(X) = R - (G + Q) \tag{8}$$

The safety index (β) is calculated as

$$\beta = -\phi^{-1}(P_f) \tag{9}$$

where

$\phi^{-1}(\ )$ is the inverse of the cumulative normal distribution; and

P_f is the probability of failure at the ultimate limit state, and is given by

$$P_f = min\begin{bmatrix} P(E \geq 1.2G_k + 0.5Q_k + 1.3W_k) \\ P(E \geq 1.2G_k + 1.6Q_k) \\ P(E \geq 1.35G_k + 1.0Q_k) \\ P(E \geq 1.35G_k) \end{bmatrix} \tag{10}$$

The load combinations are as recommended in SANS 10160 [3]. A Monte Carlo simulation was performed to determine P_f for parametric values of wind load ratios ($\propto$) and dead load ratios (ξ) defined as:

$$\propto = \frac{W_k}{G_k + Q_k + W_k} \tag{11}$$

and

$$\xi = \frac{G_k}{G_k + Q_k} \tag{12}$$

The statistics of load effects assumed in this analysis are obtained from Kemp et. al. [10] and Retief and Dunaiski [11] 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) 'Lifetime max'	0.71	0.24	Gumbel Type I
Live (office) 'Point-in-time'	0.68	0.25	Gumbel Type I
Wind 'Lifetime max'	0.70	0.35	Gumbel Type I

The results of this calibration are given in figures 1, 2, 3 and 4 for wind load ratios of 0, 0.2, 0.4 and 0.6 respectively. In the figures, the safety index β is plotted as a function of the dead load ratio. From the figures, it is apparent that the load factors and load combination factors achieve a uniform safety index of 2.7 over the practical range of ratios of dead, live and wind loading (as provided by the envelope of the safety index). For cold-formed steel, the dead load ratio is in the order of 0.10 to 0.30. The target safety index as required in SANS 10160 [3] is $\beta_T = 3.0$.

For wind load ratio less than 0.4, the $1.35G_k + 1.0Q_k$ combination dominates for dead load ratios greater than approximately 0.8 as shown in figure 1.

$$\text{i.e.: } \frac{G_k}{G_k+Q_k} > 0.8 \Rightarrow G_k > 4Q_k \tag{13}$$

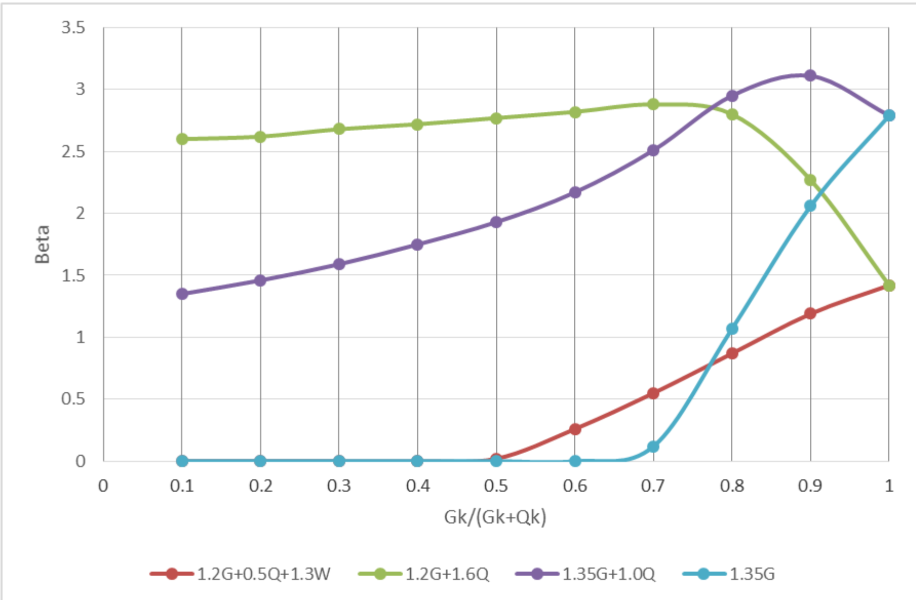

Figure 1: Variation of Safety Index β for Wind Load Ratio $\propto = 0$

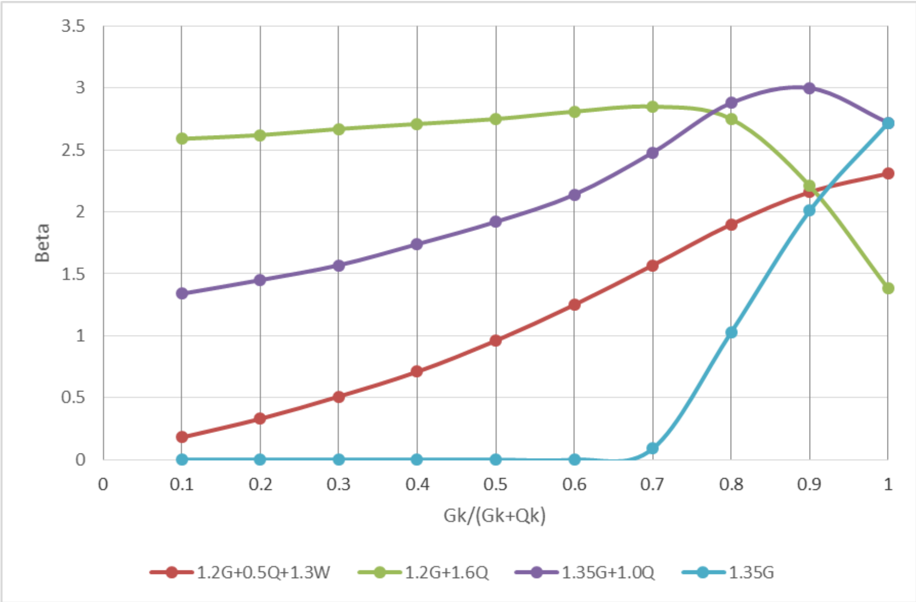

Figure 2: Variation of Safety Index β for Wind Load Ratio $\propto = 0.2$

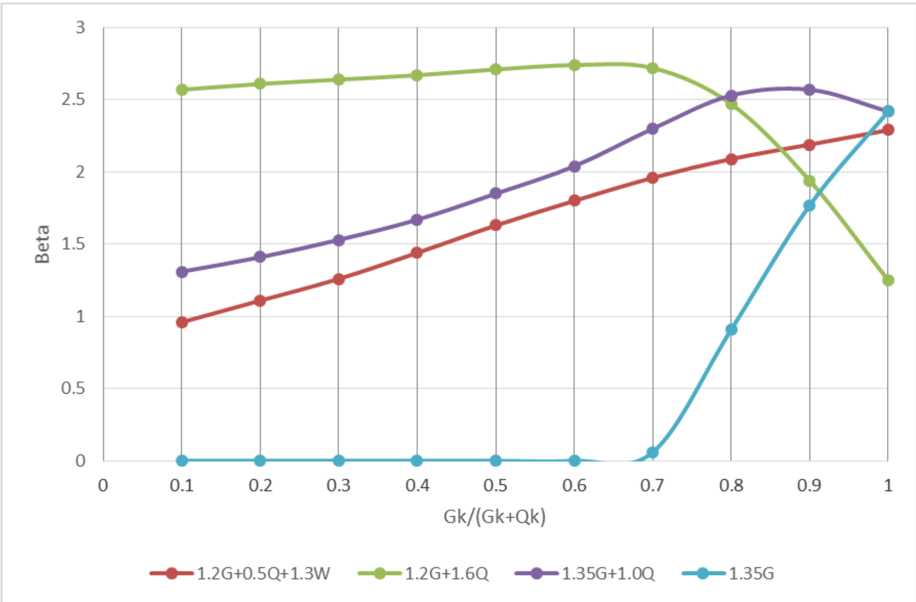

Figure 3: Variation of Safety Index β for Wind Load Ratio $\propto = 0.4$

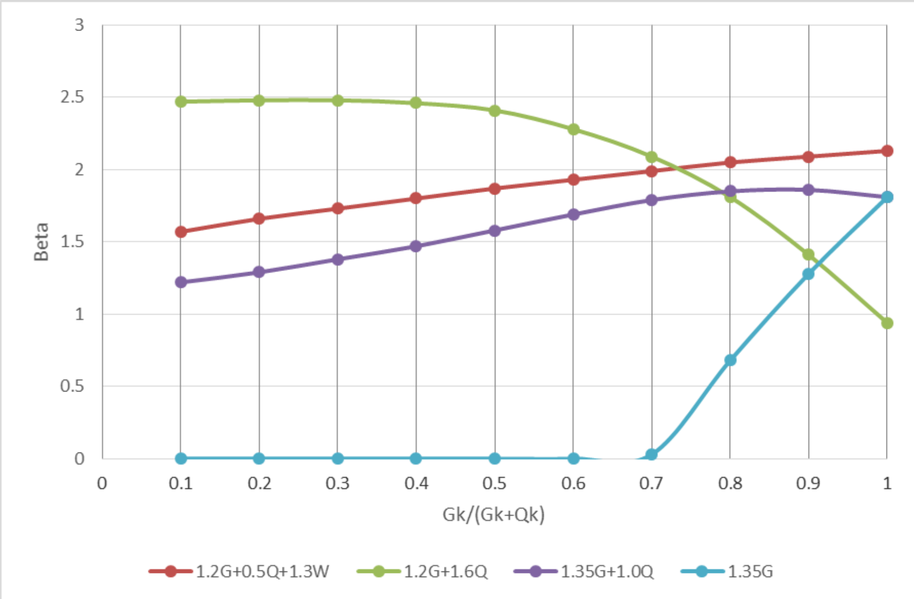

Figure 4: Variation of Safety Index β for Wind Load Ratio $\propto = 0.6$

The above result is in line with the observation made by Retief and Dunaiski [11] using the GSF approach. However, for wind load ratio greater than 0.6, the $1.2G_k + 0.5Q_k + 1.3W_k$ dominates for dead load ratio greater than 0.74. This occurs when

$$G_k > 2.85Q_k \tag{14}$$

The above check has not been included in the SANS10160 [3] and may control the design in the case of high wind load ratios. However, for practical ranges of dead load ratios for cold-formed steel, this case may not be critical. The safety index for wind load ratio equal to 0.6 is between 2.0 and 2.5.

2.2 Materials Resistance Calibration

In this paper, further consideration and calibration is made of a cold-formed member subject to bending. The section moment capacity is that of a section with stiffened or partially stiffened compression flanges. SANS 10162-2 [2] requires that the design bending moment (M*) of a flexural member shall satisfy the following

$$M^* \leq \emptyset_b M_s \tag{15}$$

$$M^* \leq \emptyset_b M_b \tag{16}$$

where;

M_s = nominal section moment capacity;

M_b = nominal member moment capacity; and

$\emptyset_b$ = capacity reduction factor for bending as presented in Table 1 of this paper.

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

A Monte Carlo simulation was performed for a cold-formed member subject to bending. The first analysis was to consider the variation in the safety index for various dead load ratios. Four values of capacity reduction factors were considered (i.e. $\emptyset$ = 0.95; 0.90; 0.85; 0.80). The results of this analysis is shown in figure 5. In this analysis, the probability distributions of the material resistance were assumed to be normal (NBS Special Publication [13]), with:

$$\frac{\bar{R}}{R_k} = 1.17 \quad and\ V_R = 0.17 \tag{16}$$

where $\bar{R}/R_k$ is the mean to characteristic resistance and V_R is the coefficient of variation. The load factors used are those indicated in equation (10) from SANS 10160 [3].

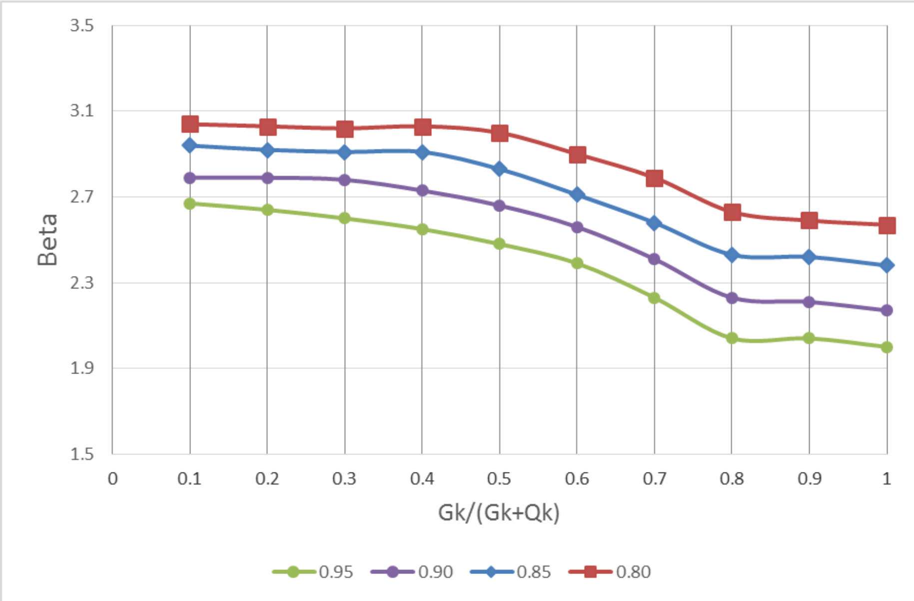

Figure 5: Variation of Safety Index β with capacity reduction factor ($\emptyset$)

It is observed from figure 5 that the safety index β is a constant for most of the practical ranges of dead load ratios between 0.1 and 0.3, and ranges from 2.7 to 3.0 for $\emptyset =$ 0.95 and 0.80 respectively. For high dead load ratios, the safety index drops to about 2.0 for $\emptyset = 0.95$. For $\emptyset = 0.90$, the safety index ranges fairly uniform from 2.4 to about 2.9. It is thus recommended that in order to attain a target safety index of 3.0, the value of $\emptyset = 0.85 - 0.90$ be adopted as opposed to the current value of 0.95. This value compares to the resistance factor $\emptyset =$ 0.90 specified by AISI [12] for LSD.

A further analysis was performed with the capacity reduction factor kept as a constant $\emptyset = 0.90$, and varying the coefficient of variation (i.e. V_R = 0.12; 0.25; 0.17; 0.19 and 0.22). The results of this analysis is shown in figure 6.

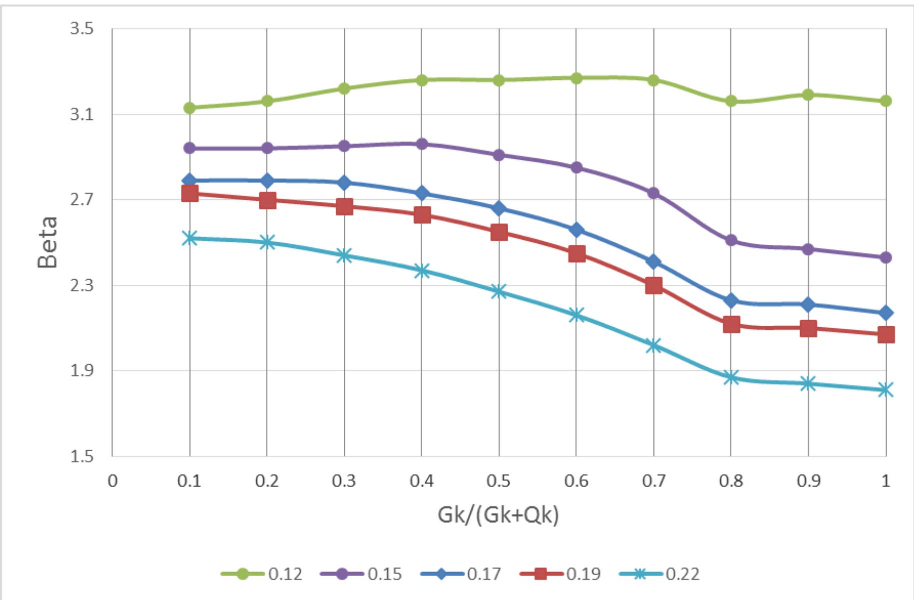

Figure 6: Variation of Safety Index β with coefficient of variation (V_R)

It is observed from figure 6 that the safety index is uniform for very low coefficient of variation. For example, for V_R = 0.12, the safety index is uniform for all dead load ratios at a value of about 3.2. However, for high coefficient of variation, V_R = 0.22, the value of β is below 2.5. Considering the levels of skills and technology advancement in South Africa compared to developed nations, a low value of V_R would be highly unlikely in South Africa. A likely V_R of 0.19 would yield a $\beta = 2.7$ for dead load ratios ranging between 0.1 and 0.3. The statistics for the material resistances would therefore need to be verified through research. However, a β value of 2.7 may be acceptable and hence support the adoption of $\emptyset = 0.90$ for member section capacity.

3. DISCUSSION

The paper has reviewed the calibration of the load factors and load combination as presented in SANS 10160 [3]. The load combination almost achieved the target reliability index of $\beta_T = 3.0$ at high dead load ratios. Although the safety index is uniform for lower dead load ratios, it is below the target safety index and as such may require to be reviewed. The load combination $1.35G_k + 1.0Q_k$ dominated for $G_k > 4Q_k$. However, for high wind load ratios and $G_k > 2.85Q_k$, the load combination $1.2G_k + 0.5Q_k + 1.3W_k$ dominates. For cold-formed steel, these load combinations would not be problematic as the practical dead load ratios are in the range of 0.1 to 0.3.

Based on the load combinations provided in SANS 10160 [3], a Monte Carlo simulation was performed for a cold-formed section under bending. The results have shown that the safety index is dependent on the capacity reduction factor and the dead load ratio. Although fairly uniform, the recommended value of $\emptyset = 0.95$ in SANS 10162-2 [2] will not provide a sufficient reliability ($\beta = 3.0$) for practical values of dead load ratios. The value of the safety index is also sensitive to the coefficient of variation (V_R), with the value of β being as low as 1.8 for high values of V_R. A value of the capacity reduction factor of $\emptyset = 0.90$ is thus recommended.

4. CONCLUSIONS

The South African cold-formed steel design SANS 10162-2 [2] was adopted from the Australian/New Zealand Standard AS/NZS4600 (2005) without calibration to the existing loading code SANS 10160 [3]. Although the load combinations show fairly uniform safety index over the practical dead load ranges, there is a need to research further on the load factors and load combinations and ensure alignment with other international codes. The capacity reduction factor $\emptyset$ for section capacity bending has shown significant difference with what is recommended in the standard, a value of 0.90-0.85 being recommended as compared to 0.95. Hence, more research is thus required to calibrate all the capacity reduction factors. This research must be backed with cold-formed materials resistance statistics research.

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