

DESIGN FOR CONCRETE CONTAINMENT STRUCTURES: RELATION BETWEEN STRENGTH AND WORKING STRESS DESIGN METHODS

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ABSTRACT

The Canadian Nuclear Standard CSA N287.3, Design Requirements for Concrete Containment Structures for Nuclear Power Plants (NPP) is currently under revision and is expected to be published in 2014. This is the fourth edition of the Canadian Standard which supersedes the previous editions published in 1978, 1982, and 1993 under the title Design Requirements for Concrete Containment Structures for CANDU NPP. These early standards were the basis for design of containment structures in Canada and abroad. This standard specifies minimum requirements for design of concrete containment structures. This Standard is written in the form of additional code requirements to the Canadian Standard A23.3-04, Design of Concrete Structures which is primarily applicable to building structures. A23.3-04 requirements for strength are based on limit state design philosophy in which the strength reduction factors, and load factors are used at ultimate. On the other hand, some other codes and standards for NPP such as ACI 359 are written based on working stress (WS) design method. In this paper, a simple relationship between the WS design method and strength design (SD) method for members subjected to flexure, shear and direct tension is developed. This relationship will help the designers to determine the limiting stresses in nuclear containment structures at service load when designed based on limit state approach. This relationship can also be used to limit the stresses in containment structures to the desired level when designed based on strength. This should help the calibration process of different nuclear codes to building codes.

INTRODUCTION

Nuclear containment structures (NCS) have traditionally been designed using the Working Stress (WS) Design Method or Alternate Design Method (as defined in Appendix A of ACI 318-95 Code (1995)). Using this approach, the stresses in non prestressed reinforcement are kept to an acceptable range for durability as well as to control cracking and leakage. However, based on the Strength Design (SD), i.e. using load factors and strength reduction factors, the resulting stress in reinforcement are much higher than what would be considered as desirable for NPP structures.

The Canadian Standard N287.3 (2014) Design Requirements for Concrete Containment Structures for NPP is currently under revision and is expected to be published in 2014. This Standard is written in the form of a additional code requirements to the Canadian Standard A23.3-04 (2004), Design of Concrete Structures which is primarily applicable to building structures. A23.3-04 requirements for strength are based on limit state design philosophy in which the strength reduction factors, and load factors are used at ultimate.

On the other hand, the design provisions of ACI 359/ASME (2007) are very different from those in ACI 318 or 349 (2006). In ACI 359/ASME, the design is based on WS, since containment structures are designed to remain elastic except for local response to impact loads to minimize cracking under design conditions that do not involve thermal accident conditions.

To reduce these effective stresses to the desired level of working stress design, a parameter referred to as serviceability design factor (SDF) can be applied to the required stress. This factor when designed based on SD method can be applied to structural members subjected to flexure, shear or direct

tension. Following a detailed analytical study supported by case studies, a simple expression is derived for determination of SDF for members subjected to flexure, shear or direct tension.

SERVICEABILITY DESIGN FACTOR (SDF) FOR FLEXURE

In this section, a simple equation for SDF for members subjected to flexure is derived. The equation is applicable to both singly and doubly reinforced sections.

To determine an appropriate value for SDF in flexure, the basic equations for flexural design for reinforcement using the Strength Design (SD) and the Working Stress (WS) design methods are used.

In this approach, all material characteristics including yield strength of steel, compressive strength of concrete, and the allowable stresses in reinforcement are considered. The results with varying material characteristics and steel ratios are considered to show the appropriate values for SDF.

Rectangular Singly Reinforced Concrete Sections Working Stress (WS) Design Method

The compression stresses in a beam section shown in Figure 1 vary linearly for zero at the neutral axis to a maximum stress of f_c at the extreme compression fibre.

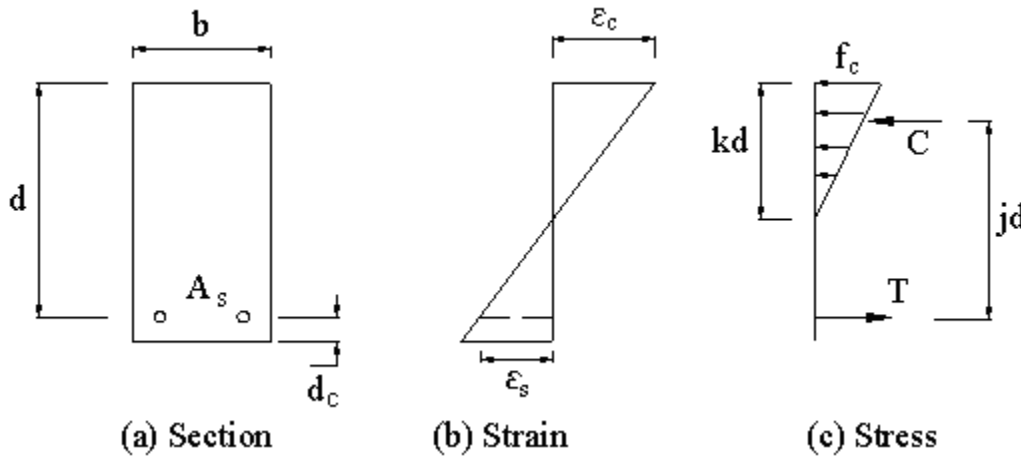


Figure 1. Strain and Stress distribution in straight line theory

Based on Figure 1, the moment at service load is:

$$M = A_s f_s j d$$

or

$$M = \frac{1}{2} f_c k j b d^2$$

Where f_s and f_c are allowable steel and concrete stresses respectively.

Comparing these equations and substituting for

$$j = 1 - \frac{k}{3}, \quad k = \sqrt{(\rho n)^2 + 2\rho n} - \rho n$$

$$n = \frac{E_s}{E_c} \quad \text{and} \quad \rho = \frac{A_s}{b d}$$

where E_s and E_c are modulus of elasticity of steel and concrete respectively and ρ is steel ratio. Then we have:

$$M = A_s f_s d \left(1 - \frac{k}{3}\right) \quad (1)$$

Strength Design (SD) Method

Based on the strength design method (using load factors and factored resistance), the linear elastic theory for stress is no longer valid. Instead an equivalent of rectangular stress block is used as shown in Figure 2.

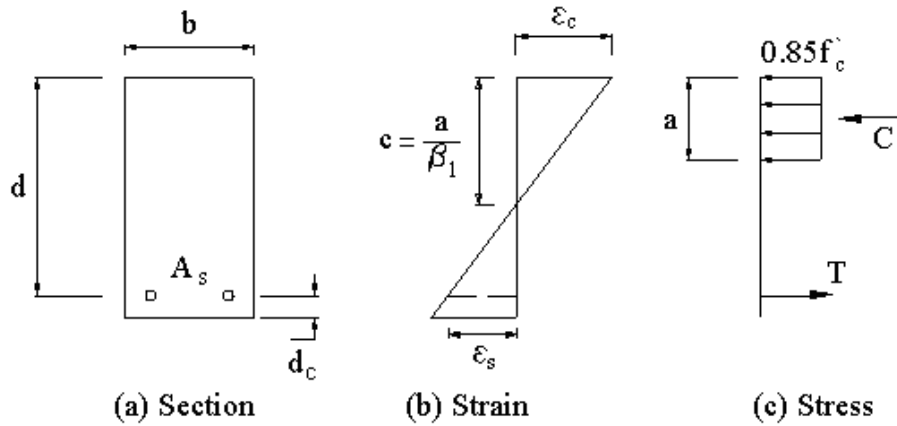


Figure 2. Strain and stress distribution – equivalent rectangular stress block

The ultimate moment is given by:

$$M_u = \Phi A_s f_y \left(d - \frac{a}{2}\right) \quad \text{where} \quad a = \frac{A_s f_y}{0.85 f_c b}$$

Where f_y and f_c are steel yield strength and concrete compressive strength respectively.

Also, $a = c \beta_1$ where $\beta_1 = 0.85$, and $\Phi = 0.9$ which is the strength reduction factor in flexure.

Substituting for a in M_u we have:

$$M_u = \Phi A_s f_y \left(d - \frac{a}{2}\right) = \Phi A_s f_y \left(d - \frac{A_s f_y}{2 \times 0.85 \times f_c b}\right)$$

Or simply:

$$M_u = \Phi A_s f_y d \left(1 - 0.59 \frac{f_y}{f_c} \rho\right) \quad (2)$$

Substituting for M and M_u from equations 1 and 2, we have:

$$\frac{M_u}{M} = \frac{\Phi f_y \left(1 - 0.59 \frac{f_y}{f_c} \rho\right)}{f_s \left(1 - \frac{k}{3}\right)}$$

The above relation can be expressed as:

$$\frac{M_u}{M} = \frac{\Phi f_y}{f_s} \alpha \quad (3)$$

where

$$\alpha = \frac{(1 - 0.59 \frac{f_y}{f'_c} \rho)}{(1 - \frac{k}{3})}$$

The moment ratio shown above represents the SDF. This ratio is a function of the steel yield strength, which is the most important parameter in SDM and the allowable steel stress, the most important parameter in WS. Also the parameter α is a function of the steel ratio, modular ratio, steel yield strength and concrete compressive strength. The effect of this parameter on SDF will be investigated. For determining the range of variability of α , a wide range of values for ρ is considered. By changing the values of f_y , f'_c the values of k and α can be computed. The value of ρ is increased up to ρ_{max} , in which:

$$\rho_{max} = 0.75 \rho_b \quad \text{where} \quad \rho_b = 0.85 \beta_1 \frac{f'_c}{f_y} \frac{87000}{87000 + f_y}$$

Where ρ_b is referred to as reinforcement ratio for a balanced cross-section (f_y and f'_c are in psi).

Figure 3 shows the variation of α with ρ . It is interesting to note that the value of α in most cases is very close to unity in the practical range of interest.

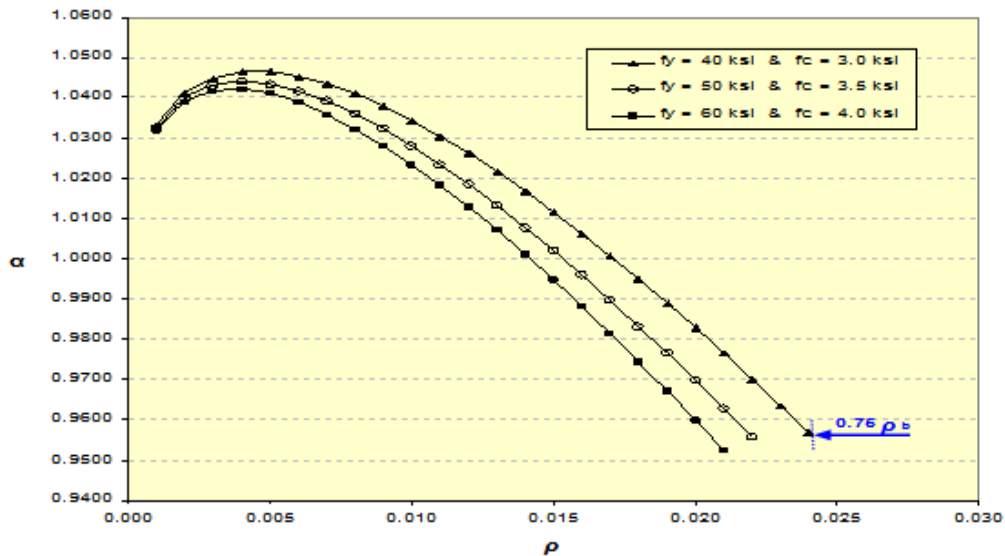


Figure 3. Variation of α material properties in tension controlled, singly reinforced section

Doubly Reinforced Concrete Sections

Reinforced concrete sections are sometimes provided with compression reinforcement. With these assumptions, the force-equilibriums will be developed in order to arrive at an equation for SDF.

In working stress design:

$$\rho_e = \rho' + \frac{n}{2r(n+r)}$$

In which:

ρ' = Compressive steel ratio, and

ρ_e = Balanced stress design, the steel ratio in which steel and concrete reaches the allowable stress.

In strength design:

$$\rho \leq \rho_{\max} = 0.75\rho_b + \rho'$$

To ensure the yielding of compressive steel we must have:

$$\rho \geq \rho_{Lim} = 0.85\beta_1 \frac{f'_c d'}{f_y d} \frac{87000}{87000 - f_y} + \rho'$$

Also the maximum strain for concrete is assumed to be 0.003.

Working Stress (WS) Design

The compression stresses in a beam section is shown in Figure 4.

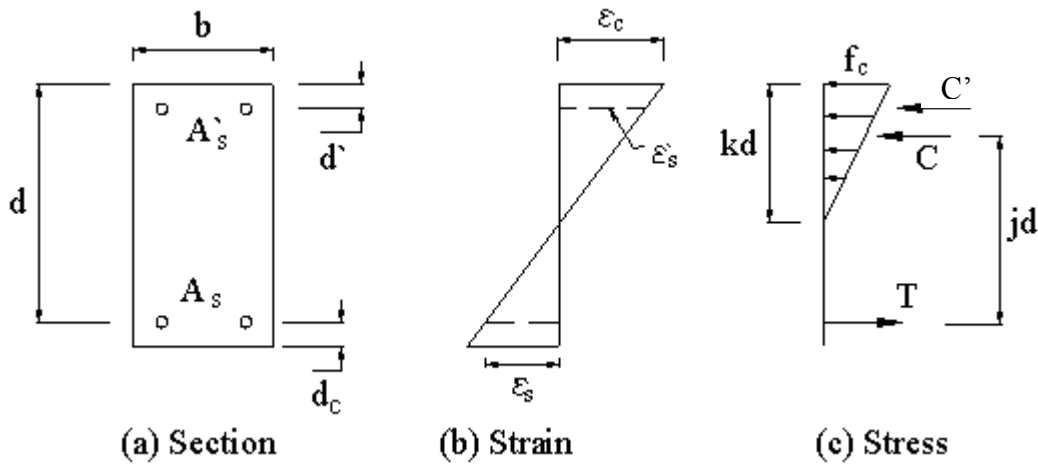


Figure 4. Strain and Stress distribution in straight line theory

With the assumptions made for singly reinforced section, the moment at service load is:

$$M = (\rho - \rho')bjd^2 f_s + \rho'b(d - d')f_s$$

By rearranging the above equation we have:

$$M = bd^2 f_s ((\rho - \rho')(1 - k/3) + \rho'(1 - d/d')) \quad (4)$$

Where f_s is the steel stress, which can be assumed as the allowable steel stress.

For locating the neutral axis or value of k , the transformed section needs to be considered. By referring to Figure 4 and setting the moment equilibrium about the neutral axis, we have:

$$j = 1 - \frac{k}{3} \quad \text{where} \quad k = \sqrt{\left((\rho + 2\rho')n\right)^2 + 2\left(\rho + \rho' \frac{d'}{d}\right)n - (\rho + 2\rho')n}$$

where $n = \frac{E_s}{E_c}$; Modular ratio

Strength Design (SD) Method

Based on the strength design method, the equivalent rectangular stress block for a doubly reinforced section is shown in Figure 5.

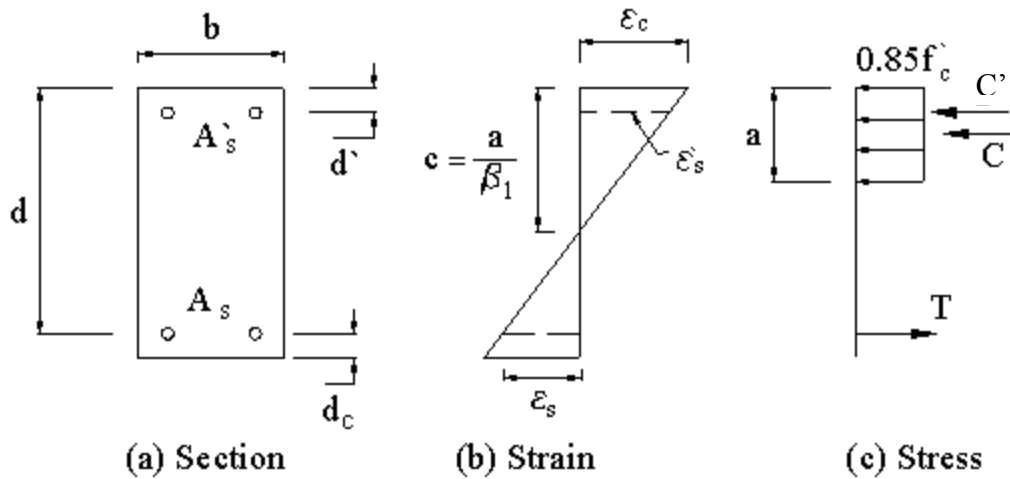


Figure 5. Strain and stress distribution – Equivalent rectangular stress block

The ultimate moment is given by:

$$M_u = \Phi \left((A_s - A_s') f_y \left(d - \frac{a}{2} \right) + A_s' f_y (d - d') \right)$$

Where

$$a = \frac{(A_s - A_s') f_y}{0.85 f'_c b}$$

Where f_y and f'_c are steel yield strength and concrete compressive strength respectively.

Also, $a = c \beta_1$ where $\beta_1 = 0.85$, and $\Phi = 0.9$ strength reduction factor in flexure

Substituting for a in M_u we have:

$$M_u = \Phi b d^2 f_y \left((\rho - \rho') \left(1 - 0.59 \frac{(\rho - \rho') f_y}{f'_c} + \rho' \left(1 - \frac{d'}{d} \right) \right) \right) \quad (5)$$

SD Versus WS

Substituting for M_u and M in equations 4 and 5 we have:

$$\frac{M_u}{M} = \frac{\Phi b d^2 f_y ((\rho - \rho') (1 - 0.59 \frac{(\rho - \rho') f_y}{f'_c} + \rho' (1 - \frac{d'}{d}))}{b d^2 f_s ((\rho - \rho') (1 - \frac{k}{3}) + \rho' (1 - \frac{d'}{d}))}$$

or

$$\frac{M_u}{M} = \frac{\Phi f_y}{f_s} \alpha \quad (6)$$

In which:

$$\alpha = \frac{(\rho - \rho') (1 - 0.59 \frac{(\rho - \rho') f_y}{f'_c}) + \rho' (1 - \frac{d'}{d})}{(\rho - \rho') (1 - \frac{k}{3}) + \rho' (1 - \frac{d'}{d})} \quad (7)$$

Similar to the case of singly reinforced concrete section, the moment ratio shown above represents SDF. This ratio is a function of the steel yield strength, and the allowable steel stress. Also the parameter α is a function of the steel ratios, modular ratio, steel yield strength and concrete compressive strength.

For determining the range of variability of α , a wide range of ρ values are considered. By varying the values of f_y , f'_c the values of k and α can be determined. The values of ρ are changed such that all constraints in the design procedure as mentioned previously are satisfied. Again, the value of α in all cases was found to be equal to or close to 1.0.

For determining the serviceability design factor for a certain load condition, we can write:

$$S_d = \frac{M_u}{\gamma M} \quad (8)$$

In which:

S_d : Serviceability design factor

M_u : Design moment based on strength design method

M : Design service (un-factored) moment

$$\gamma = \frac{w_u}{w} = \frac{\text{Factored load}}{\text{Unfactored load}} \quad (9)$$

Substituting the eqn. for M_u and M for equations (3) and (6), the SD factor, can be written as:

$$S_d = \frac{\Phi f_y}{\gamma f_s} \alpha \quad (10)$$

For design purposes, the above equation can simply apply to each load condition and related load factor. Also based on the results obtained for α , it can be assumed that this value is equal to unity:

Finally, the recommended and simplified design equation for SDF is:

$$S_d = \frac{\Phi f_y}{\gamma f_s} \quad (11)$$

SERVICEABILITY DESIGN FACTOR FOR SHEAR

In this study, the requirements by ACI 318-95 (1995) for design shear strength are first defined based on the SD. The WS design procedures for shear are also defined. Based on design procedures using both SD and WS design, it is concluded that the major factors affecting the SDF are steel yield strength, strength reduction factor, ϕ , load factor, and the steel allowable working strength. The SDF derived here is applicable to reinforced concrete shear resistance in excess of that carried by concrete alone.

Based on ACI 318-95 (1995), in Working Stress (WS) Design:

$$\frac{A_V}{s} = \frac{V - V_c}{f_s d}$$

$$V_c = 1.1 \sqrt{f'_c} b_w d$$

$$\left(\frac{A_V}{s}\right)_{\text{WSD}} = \frac{V - 1.1 \sqrt{f'_c} b_w d}{f_s d} \quad (12)$$

Based on ACI 318-95, in Strength Design (SD) method:

$$\frac{A_V}{s} = \frac{V_s}{f_y d}$$

$$V_u = \Phi V_s + \Phi V_c$$

$$V_s = \frac{V_u}{\Phi} - V_c$$

$$\left(\frac{A_V}{s}\right)_{\text{SDM}} = \frac{\frac{V_u}{\Phi} - 2 \sqrt{f'_c} b_w d}{f_y d} \quad (13)$$

The SDF is defined as the ratio of the above equations (12) and (13):

$$S_d = \frac{\left(\frac{AV}{s}\right)_{WSD}}{\left(\frac{AV}{s}\right)_{SDM}} = \frac{\frac{V-1.1\sqrt{f'_c}b_wd}{f_s d}}{\frac{\frac{V_u}{\Phi}-2\sqrt{f'_c}b_wd}{f_y d}} = \frac{f_y}{f_s} \frac{V-1.1\sqrt{f'_c}b_wd}{\frac{V_u}{\Phi}-2\sqrt{f'_c}b_wd} \quad (14)$$

Equation 14 can be simplified to that shown in equation 10. The SDF depends on material properties, (f_y, f_s, f'_c), shear force in member, (V, V_u) and the dimensions of member, (b_w, d).

A sensitivity study was conducted to determine the effect of the above parameters on SDF. This was done with the aid of several design examples. Results of the study showed that for all cases, a value of unity can be assigned to α . Figure 6 shows variation of the S_d factor for different material parameters. This figure shows that the assigned value of α to unity is appropriate in the proposed equation 10. This indicates that the SDF depends on f_y, f_s and load factor (γ). Therefore, the equation for the SDF is the same as equation 11.

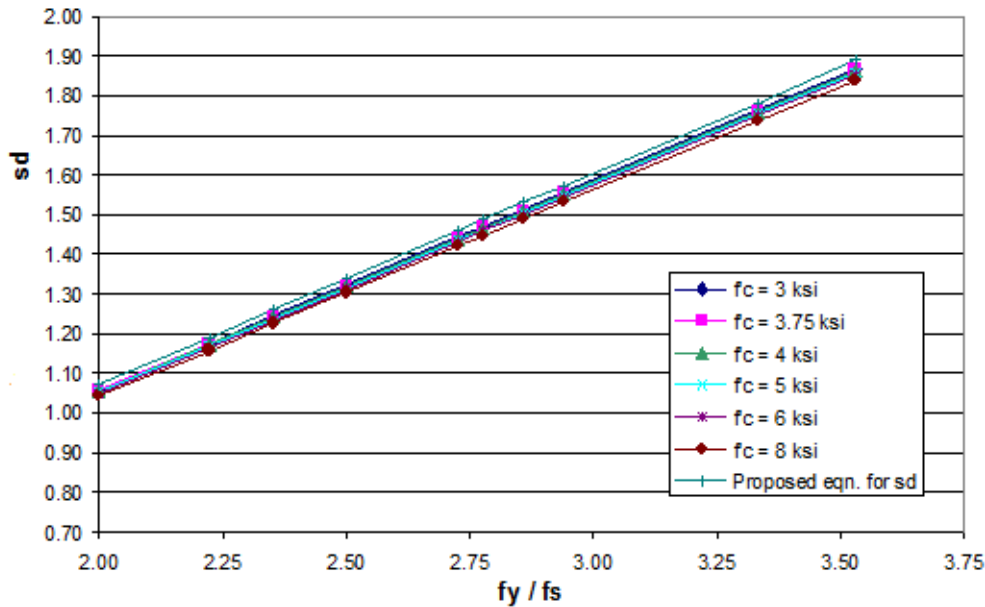


Figure 6. Serviceability design factor for different material properties

SERVICEABILITY DESIGN FACTOR FOR DIRECT TENSION

To derive an equation for SDF for members subjected to direct tension, a similar procedure as that used for flexure and shear is used. The equations for WS and SD methods are used.

The SDF is expressed as:

$$S_d = \frac{\left(A_S\right)_{WSD}}{\left(A_S\right)_{SDM}} = \frac{\frac{T}{f_s}}{\frac{T_U}{\Phi \cdot f_y}} = \frac{\Phi}{T_U} \frac{f_y}{f_s} = \frac{\Phi}{\gamma} \frac{f_y}{f_s} \quad (15)$$

where

$$\gamma = \frac{T_u}{T}$$

where T and T_u are the unfactored and factored applied tensile loads respectively.

Therefore, the equation 16 for SDF is similar to that shown in equation 10. Therefore, the derived equations for SDF can be expressed in a simplified general form to include all possible cases including flexure, shear and tension as follows.

$$S_d = \frac{\phi \times f_{s_SDM}}{\gamma \times f_{s_WSD}} \times \alpha \quad (16)$$

where α is equal to 1.0

CONCLUSION

Current nuclear and building codes use different approaches for concrete design. The widely different approaches do not allow comparisons of these codes. This limit the usefulness of these codes since it is not clear how to apply them to different practices in different countries where national codes are required to be used. For nuclear containment structures designed in Canada, safety is at the heart of the design approach without undue conservatism. In this paper a general methodology is presented to calibrate and compare different codes which are using different methodologies. This provides a key (or a Rosetta stone) by which one can compare the level of protection achieved by different codes without resorting to lengthy and expensive detailed designs. A simple equation is derived to find the relation between the strength design and working stress design methods. This equation can be applied to members subjected to flexure, shear, and tension.

ACKNOWLEDGEMENTS

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