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Comparison between reinforced concrete designs based on the ACI 318 and BS 8110 codes

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Abstract. Municipalities in the United Arab Emirates approve reinforced concrete design of building structures to follow either the ACI 318 or the BS 8110 code. Since the requirements of these codes are different from each, there is a need to compare the structural demand in the two codes. The main objective of this study is to compare the design requirements of the ACI 318 code with the BS 8110 code for the flexural, shear and axial compression limit states. The load factors and load combinations in the two codes are also compared. To do so, a large number of cross-sections with different geometries, material properties, and reinforcement ratios are analyzed following the procedures in the two codes. The relevant factored load combinations in the two codes are also investigated for a wide range of live-to-dead load ratios and for various wind-to-dead load ratios. The study showed that the differences between the design capacities in the ACI 318 and BS 8110 codes are minor for flexure, moderate for axial compression, and major for shear. Furthermore, the factored load combinations for dead load, live load and wind in the two codes yield minor-to-moderate differences, depending on the live-to-dead load ratio and intensity of wind.

Keywords: axial compression; code; concrete; flexure; reinforced concrete; shear; specification; standard; structural design

1. Introduction

Comparative studies related to structural codes, standards and specifications are not uncommon in the available literature. Often these studies are concerned with comparison of nominal loads, load combinations, load factors, resistance factors, and expressions for resistances for various limit states and structural types. Introduction of new structural codes, design philosophies, and materials also prompt research on comparative studies between structural design codes. Such studies provide insight into the various approaches to codified structural design in various countries and point to what extent one code differs or agrees with another code with regard to the level of accuracy, safety, complexity and details. They are also useful in countries where more than one code is allowed to be used for structural design, as they help in determining which code has a higher factor of safety than another.

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2. Literature review

Research work related to comparisons between structural codes is numerous in the available literature. In the recent past, codes in North America have changed their design philosophy from an Allowable Stress Design (ASD) format to a Load and Resistance Factor Design (LRFD) format in order to achieve uniform safety. For steel structures, the American Institute of Steel Construction published its first LRFD specification in 1986. This step provoked several studies comparing the ASD with the LRFD codes (Zhou and Chen 1984, Lindsey 1984, Roeder 1990, Heger 1993, Soulages *et al.* 1996).

In 1994, AASHTO introduced its first edition of the LRFD bridge design specification, intended to eventually replace the standard specification. The new reliability-based specification considered technological advances in bridge engineering, sound scientific principles, and systematic approach to ensure safety, serviceability, inspectability, economy and aesthetics (Lwin 1999). This development encouraged studies comparing designs based on the old specification philosophy with the new one (Tabsh 1996, Shahawy and Batchelor 1996, Nowak *et al.* 1999, Nielsen and Schmeckpeper 2002, Miller and Durham 2008). The published work contributed to enhancements in the subsequent editions of the specification.

In 1996, the structural wood design industry responded to the emerging preference to change from an ASD to LRFD code philosophy by publishing its first LRFD manual for engineered wood construction (American Forest and Paper Association 1996). Shortly thereafter, many studies identified similarities and differences between the old and new code requirements (Showalter *et al*. 1998, Warren *et al*. 1998). A comprehensive examination of the ASD and LRFD codes for axially loaded members, flexural components, and connections was conducted in 2000 by Pellicane and Criswell (2000a, b) and by Pellicane (2000).

When a design procedure in one code is different from others, comparative research into the various procedures is often carried out to determine which procedure is more accurate. For example, as there are differences in the design of procedures of concrete-filled steel tubular columns among the different structural codes around the world, there has been plenty of research work on the subject (Zhang and Shahrooz 1999, Al-Rodan 2004, Ma and Zhang 2007).

With regard to comparisons between reinforced concrete design provisions in the various international codes, several research studies have been conducted on the subject. However, most of the published work on the ACI 318 code (ACI318M-11 2011) and other international standards addresses specific issues, such as crack width (Ganesan and Shivananda 1996), shear behavior of deep beams (Tan and Lu 1999), deflection (Malhas and Rahman 2003), and compression members (Tong *et al.* 2011). Comprehensive comparisons between the ACI 318 code and other international codes are limited in the literature (Zachar and Naik 1996, Hawileh *et al.* 2009), and none are with the British Standard. Hence, the current study fulfills a need that is lacking in this area.

3. Problem statement

Most countries generally require structural design to follow one code or specification. For example, reinforced concrete design is accomplished following the ACI 318 code (ACI318M-11 2011) in the United States, the CAN/CSA-A23.3 (2004) standard in Canada, Eurocode-EC2 (2002) in Europe, and AS3600 (2009) in Australia. However, there are some countries around the world that approve structural design to be based on one of a number of codes. One of these countries is the United Arab Emirates (UAE), which approves reinforced concrete design of building structures to follow either the ACI 318 or the BS 8110 code (1997). Although the British Standard is currently being phased out in the UK due to the introduction of the Eurocode EC2, this is not the case in the UAE where the BS 8110 is still commonly used by a large number of consultants.

Back in the 1980s and 1990s, most of the structural concrete design in the UAE was done by UK-educated engineers or UK expatriates following the BS 8110 code. With the unprecedented growth in the construction sector in the past decade, many American structural engineering consultants started establishing new offices in the country and aggressively pursued building development projects. With this trend, many concrete buildings started to be designed following the ACI 318 code. This was helped by the fact that local municipalities and departments of public work allowed either code to be used for the design of new structures. Today, it is estimated that both the ACI 318 and BS 8110 are just about equally followed for reinforced concrete design in the UAE. Since the design necessities of the ACI 318 and BS 8110 codes are different from each, there is a need to compare the structural demand in the two codes and determine which one has higher factor of safety for a given limit state.

4. Objectives and scope

The main goal of this study is to compare the design requirements of the American ACI 318 code with the British BS 8110 code. Specifically, the flexural, shear and axial compressive capacity of members are considered. Also, the load factors and load combinations in the two codes are compared. To achieve the stated objectives, a large number of cross-sections with different width-to-depth ratios (0.5-2), material properties (concrete cube strength=20-55MPa, steel yield strength=250MPa or 450MPa), and reinforcement ratios (longitudinal steel reinforcement ratio for flexure ρ=0.005-0.050, transverse steel reinforcement ratio for shear ρ_v=0.002-0.012, and gross longitudinal reinforcement ratio for columns ρ_g=0.005-0.08) are analyzed by the two codes for the three considered limit states. The study considers the relevant factored load combinations in the two codes with a wide range of live-to-dead load ratios (L/D=0-5) and for various wind-to-dead load ratios (W/D=0, 0.125, 0.25, 0.5, and 1).

5. Background on structural design

In this section, the American Concrete Institute's ACI 318 and the British Standard's BS 8110 code requirements for flexure, shear and axial load are briefly outlined. Only rectangular cross-sections with rectilinear stirrups and ties are covered. Also, doubly reinforced beams, slender columns, and columns subjected to eccentric loading, are not addressed. It should be noted that the ACI 318 code provisions are based on the concrete cylinder strength, f'_c, whereas the BS 8110 code equations depend on the concrete cube strength, f_{cu}. Further, the ACI 318 code uses one resistance factor applied to the nominal capacity, unlike the BS 8110 which utilizes partial factors applied to the material strength properties.

5.1 ACI 318

Flexural design of beams in the ACI 318 code assumes an ultimate compressive strain in the concrete equal to 0.003. For under-reinforced concrete sections, the stress in the steel reinforcement is equal to the yield stress, f_y (MPa), and the compressive stress in the concrete is simplified as a block of constant intensity equal to $0.85f'_c$, where f'_c is the 28-day compressive strength of a cylinder. The nominal flexural capacity, M_n (N-mm), can be obtained from (Wight and MacGregor 2011)

$$M_n = A_s f_y \left(d - 0.59 \frac{A_s f_y}{f_c' b}\right) \tag{1}$$

where A_s = area of tensile reinforcement (mm^2), d = effective depth of reinforcement from extreme compressive fibers (mm), and b = width of the beam (mm). In the ACI 318 code, the strength reduction factor for flexure, ϕ, depends on the strain in the steel layer closest to the tension side, ε_t. For tension-controlled regions ($\varepsilon_t \geq 0.005$) $\phi = 0.90$, for compression-controlled regions ($\varepsilon_t \leq \varepsilon_y$) $\phi = 0.65$, and for transition-regions ($\varepsilon_y < \varepsilon_t < 0.005$) ϕ linearly varies between 0.65 and 0.90. To ensure adequate ductility in the design of new structures, the code requires $\varepsilon_t \geq 0.004$; in this case, ϕ ranges between 0.81 and 0.90.

In the ACI 318 code, the nominal shear strength of a section transversely reinforced with stirrups, V_n (N) is (ACI318M-11, Eq. (11)-(2))

$$V_n = V_c + V_s \tag{2}$$

where V_c (N) is the shear strength provided by the concrete (ACI318M-11, Eq. (11)-(5))

$$V_c = \left(0.16\,\lambda\sqrt{f_c'} + 17\rho_w\left(\frac{V_u d}{M_u}\right)\right) b_w d \leq 0.29\sqrt{f'_c}\, b_w \tag{3}$$

and V_s (N) is the shear strength contributed by the stirrups (ACI318M-11, Eq. (11)-(15))

$$V_s = \frac{A_v f_{yt} d}{s} \tag{4}$$

where λ = factor that accounts for the density of concrete, ρ_w = is the flexural reinforcement ratio given by $A_s/(b_w d)$, b_w = narrowest width of the cross-section (mm), V_u = critical factored shear (N), M_u = factored moment concurrent with V_u (N-mm), A_v = total area of vertical stirrups per spacing (mm^2), f_{yt} = yield strength of the steel stirrups (MPa), and s = spacing of stirrups along the beam length (mm). The upper limit on the quantity ($V_u d/M_u$) is 1.0. The strength reduction factor for shear is $\phi = 0.75$.

The ACI code accounts for minimum eccentricity in the determination of the nominal capacity of tied columns in pure axial compression, P_n (N), by reducing the theoretical capacity by 20% (ACI318M-11, Eq. (10)-(2))

$$P_n = 0.8[0.85 f_c'(A_g - A_{st}) + A_{st} f_y] \tag{5}$$

where A_g = gross cross-sectional area of the column (mm^2), and A_{st} = total area of longitudinal steel (mm^2). The strength reduction factor for tied columns subjected to concentric axial compression is $\phi = 0.65$.

5.2 BS 8110

Flexural design in the BS 8110 code assumes an ultimate compressive strain in the concrete equal to 0.0035. Unlike the ACI code, the British code employs partial material safety factors (equal to 1.5 for concrete and 1.15 for steel) applied as divisors to the concrete cube strength, f_{cu}, and the steel yield strength, f_y. The compressive stress in the concrete at ultimate is simplified as a block of constant intensity equal to $0.67f'_{cu}/1.5$. According to the code, the required area of steel reinforcement, A_s, for a rectangular section subjected to a factored moment, M_u, is (BS 8110, section 3.4.4.4)

$$A_s = \frac{M_u}{0.95 f_y z} \tag{6}$$

where z is the moment arm (mm) within the cross-section, calculated from (BS 8110, section 3.4.4.4)

$$z = d\left(0.5 + \sqrt{0.25 - \frac{M_u}{0.9 f_{cu} b d^2}}\right) \leq 0.95d \tag{7}$$

Similar to ACI 318, the BS 8110 code bases the design shear strength, V, inclusive of the resistance factors, of a reinforced concrete section on the contributions of both the concrete and stirrups (BS 8110 sections 3.4.5.3 and 3.4.5.4)

$$V = \left[\frac{0.79\left(\frac{100A_s}{b_v d}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4}\left(\frac{f_{cu}}{25}\right)^{1/3}}{\gamma_m} + \frac{0.95 f_{yv} A_{sv}}{s_v b_v}\right] \tag{8}$$

where $b_v = b_w$, $A_{sv} = A_v$, $f_{yv} = f_{yt}$ (as defined earlier) and γ_m is a material factor = 1.25. Note that the code imposes limits on some of the quantities in the above equation: $(100A_s/b_v d) \leq 3$, $(400/d)^{1/4} \geq 1$, and $(f_{cu}/25) \leq 1.6$.

The design capacity, P (N), of columns subjected to pure axial compression in the BS 8110 code is equal to (BSI8110 1997, Eq. (38))

$$P = 0.4 f_{cu}(A_g - A_{sc}) + 0.8 A_{sc} f_y \tag{9}$$

where $A_{sc} = A_{st}$ (as defined earlier) and all other variables have been defined earlier.

6. Background on factored load combinations

When loads from different sources are applied on a structural member, the possibility of simultaneous occurrence of extreme loads can be negligibly small. One such combination could include maximum live load, heavy snow, high wind storm, plus a major earthquake. It is possible that a few of the loads within the group could occur at the same time, but not all. Therefore, structural design codes consider realistic load combinations for use in design. The load combinations were developed to ensure essentially equal exceedance probabilities for all combinations (Nowak and Collins 2000).

The loads used in the design for ultimate strength are nominal values multiplied by load factors that are included in the various codes of practice. With this approach, the specified loads will rarely be exceeded during the useful life of the structure. The load factors, together with the strength resistance factors, provide the overall factor of safety against strength failure.

The load combinations in the ACI 318 code are based on the ASCE7 standard (ASCE7 2010). The factored load combinations involving service dead load (D), floor live load (L), roof live load

(L_r) and wind (W) in the ACI 318 code are presented below

$$\begin{gathered} 1.4D \\ 1.2D + 1.6L + 0.5L_r \\ 1.2D + 1.6L_r + (L \; or \; 0.8W) \\ 1.2D + 1.6W + 1.0L + 0.5L_r \\ 0.9D + 1.6W \end{gathered} \tag{10}$$

The corresponding load combinations in the BS 8110 code for the considered loads are shown below

$$\begin{gathered} 1.4D + 1.6L \\ 1.4D + 1.4W \\ 1.0D + 1.4W \\ 1.2D + 1.2L + 1.2W \end{gathered} \tag{11}$$

Note that the ACI 318 code differentiates between floor live load (L) and roof live load (L_r), whereas the BS 8110 code does not distinguish between the two live loads components and applies the same load factor to both.

7. Results

The approach followed in this study consisted of determining the factored (design) capacity of 400 cases covering a wide range of cross-sections and material properties analyzed by both the ACI 318 and BS 8110 codes. The ratio of the factored design capacity computed by the ACI 318 code to the corresponding capacity calculated by the BS 8110 code is then computed for all the considered cases. The results are presented graphically showing the design capacity ratio for the two considered codes versus the relevant design parameters for the three considered limit states. As the ACI code equations are based on the concrete cylinder strength, f'_c, and the BS equations are based on the concrete cube strength, f_{cu}, a conversion factor equal to $f'_c = f_{cu}/1.2$ is utilized in this study (BSI1881 1983).

7.1 Flexure

The analysis considers rectangular, singly-reinforced cross-sections with width-to-depth ratios varying between 0.5 and 2.0. Two grades of reinforcing steel are considered, with yield strengths 250 MPa and 460 MPa. The strength of cubic concrete specimen varies between 20 and 50 MPa, which corresponds to cylindrical concrete specimen strength in the range of 17-42 MPa. For a given cross-section, the approach followed in the study requires determining the factored flexural capacity based on both the ACI 318 code (from Eq. (1), with inclusion of ϕ) and BS 8110 code (from Eq. (6)), denoted respectively by M_{ACI} and M_{BS}. Based on the flexural analysis of 180 design cases, it was found that design capacity ratio, M_{ACI}/M_{BS}, correlates well with the tension steel reinforcement index, $\rho f_y/f'_c$. This index is an indicator of the flexural brittleness of the cross-section; the larger the index is, the smaller the inherent ductility. In this study, the tension reinforcement index for the considered cases ranges between 0.0125 and 0.25. In general, the findings, shown in Fig. 1, indicate that the ACI 318 and BS 8110 codes give similar results. For cross-sections with $z/d > 0.95$ (or $\rho f_y/f'_c < 0.056$) where z is the moment arm (obtained by Eq. (7))

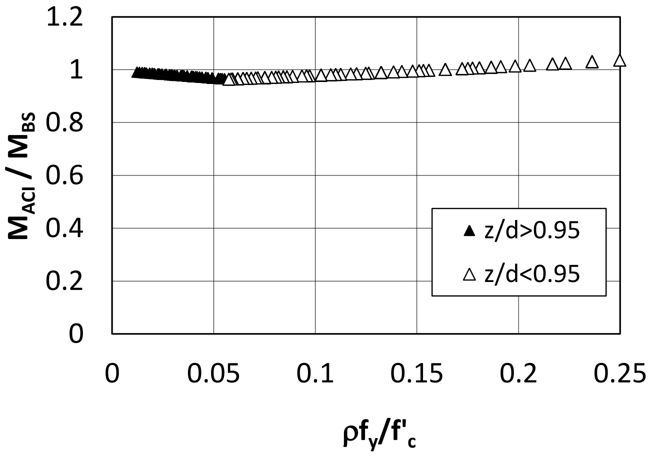

Fig. 1 Flexural capacity ratio versus tension steel reinforcement index

and d is the effective reinforcement depth from the extreme compressive fibers, Fig. 1 suggests that the design capacity ratio M_{ACI}/M_{BS} slightly decreases with an increase in the tension reinforcement index. However, the opposite is true for sections with z/d < 0.95 (or $\rho f_y/f'_c$ > 0.056). In all cases, the M_{ACI}/M_{BS} ratio generally varies within a relatively narrow range, 0.96-1.03. This indicates that both codes closely predict flexural capacity of under-reinforced sections.

7.2 Shear

The analysis considers rectangular cross-sections with width-to-depth ratios varying between 0.5 and 2.0. Two grades of stirrups steel are used, with yield strengths 250 MPa and 460 MPa. The cube strength of concrete, f_{cu}, varies between 20 and 50 MPa. The flexural reinforcement in the sections, ρ, corresponds to an effective reinforcement ratio between 0.005 and 0.04. In Eq. (3), the quantity ($V_u d/M_u$) was taken equal to its extreme value, 1.0, since at the critical location for shear, located at d-away from the face of support, the factored moment corresponding to V_u is often very small. The considered cases resulted in a stirrup reinforcement ratio, $\rho_v=A_v/(sb)$, ranging between 0.5 and 3.5. For a given cross-section, the approach followed in the study requires determining the factored shear capacity based on both the ACI 318 code (from Eq. (2), with inclusion of ϕ) and BS 8110 code (from Eq. (8)), denoted respectively by V_{ACI} and V_{BS}. Summary of the analysis of 150 design cases is shown in Fig. 2, where the design capacity ratio, V_{ACI}/V_{BS}, is plotted against the shear reinforcement index, $\rho_v f_{yt}/f'_c$. This index is indicative of the ratio of shear strength contributed by stirrups to the corresponding strength contributed by concrete. Plotting the ratio V_{ACI}/V_{BS} against $\rho_v f_{yt}/\sqrt{f'_c}$ showed a similar trend; thus, it is not considered in the study. The results are presented in Fig. 2 and show some discrepancies between the shear strengths obtained by the ACI 318 and BS 8110 codes. Except for very lightly transversely reinforced sections, Fig. 2 indicates that the ACI 318 code shear strength equations predict lower capacity than the corresponding equations in the BS 8110 code. For the common range of application, where $\rho_v f_{yt}/f'_c$ lies between 0.05 and 0.10, the ACI code yields 10-30% lower shear strength values than the BS code.

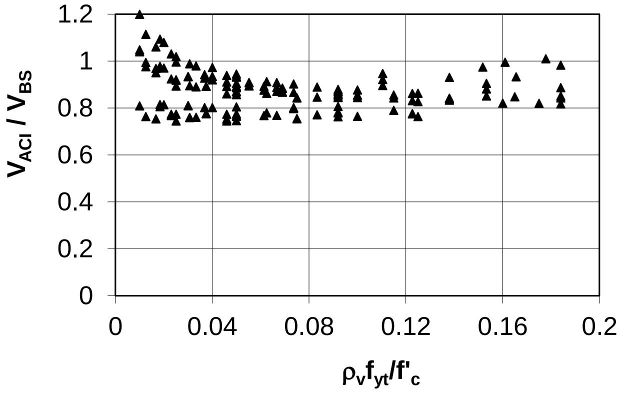

Fig. 2 Shear capacity ratio versus shear reinforcement index

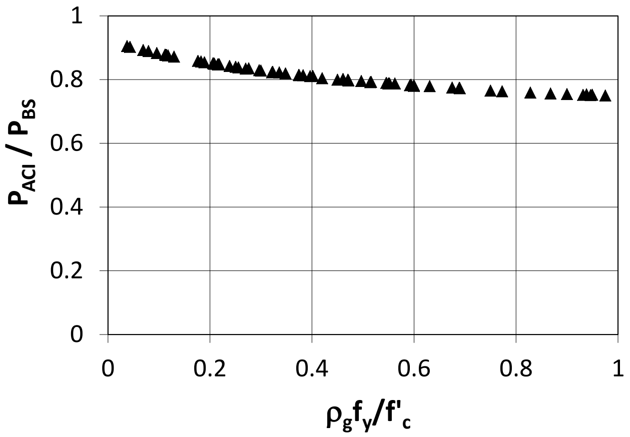

Fig. 3 Axial compression capacity ratio versus gross steel reinforcement index

7.3 Axial compression

Symmetrically reinforced, square cross-sections subjected to concentric axial compression are considered. Two grades of reinforcing steel with yield strengths of 250 MPa and 460 MPa are utilized. The cubic strength of concrete varies between 20 and 55 MPa. The considered cases resulted in gross reinforcement ratio, $\rho_g=A_{st}/A_g$ where A_g is the gross cross-area, ranging between 0.005 and 0.08. For a given cross-section, the approach followed in the study requires computing the factored axial compression capacity based on both the ACI 318 code (from Eq. (5), with inclusion of ϕ) and BS 8110 code (from Eq. (9)), denoted respectively by PACI and PBS. Summary of the analysis of 70 design cases is shown in Fig. 3, where the design capacity ratio, P_{ACI}/P_{BS}, is plotted against the gross steel reinforcement index, $\rho_g f_y/f'_c$. This dimensionless index is proportional to the ratio of the compressive capacity contributed by the steel reinforcement to that contributed by concrete. The results, presented in Fig. 3, show that as $\rho_g f_y/f'_c$ increases, the ratio of the axial compressive strength predicted by the ACI 318 code to the corresponding strength predicted by the BS 8110 code decreases. For very lightly reinforced sections, Fig. 3 indicates that the ACI 318 code axial compression strength equations result in lower capacity than the

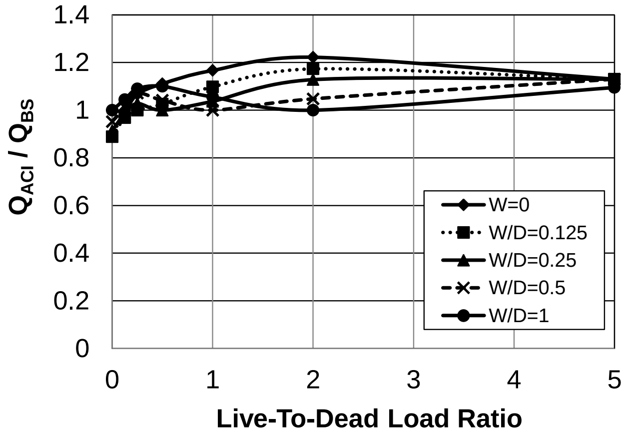

Fig. 4 load ratio versus live-to-dead load ratio for various wind intensities

corresponding equations in the BS 8110 code by about 10%. When $\rho_g f_y/f'_c$=0.4, both codes estimate the compressive capacity at an equal level. For heavily reinforced cross-sections, the ACI 318 code predicts lower design capacity than the BS 8110 code by up to 25%.

7.4 Factored load combinations

The study showed that the factored load combinations for service dead load, live load and wind presented in Eqs. (10) and (11) for the ACI 318 and BS 8110 codes, respectively, yield different results, depending on the live-to-dead load ratio and extent of wind load. Eqs. (10) and (11) show that for the load combination that includes only dead and live loads, the BS code has a larger dead load factor (1.4) than the ACI code (1.2). The live load factor in such combinations is the same in both codes (1.6). For the combinations that involve dead, live and wind loads, there are large differences in the load factors that are applied to the various loads in the considered codes. In general, the ACI code appears to have larger load factors than the BS code. Eqs, (10) and (11) indicate that the load combinations that include just dead load and wind are not treated the same way by the two codes. Fig. 4 shows the factored combined load ratio between the two codes, Q_{ACI}/Q_{BS}, plotted against the live-to-dead load ratio, *L/D*, for a wide spectrum of wind-to-dead load ratios, *W/D*. For structures subjected to negligibly low live load, the BS 8110 load combinations give slightly larger factored loads than the ACI 318 load combinations. For live-to-dead load ratios in the range 0.5-4.0, the load combinations in the ACI code yield larger factored loads than those in the BS code, especially for small wind-to-dead load ratios. For significantly large live-to-dead load ratios, the ACI code results in about 10% higher factored load than the BS code, irrespective of the extent of wind load.

9. Conclusions

The results of the study on the ACI 318 and BS 8110 codes lead to the following conclusions:

• Both codes closely predict the flexural capacity of singly-reinforced cross-section to within

4%.

• There are somewhat large discrepancies between the shear strengths obtained by the two codes. Except for very lightly transversely reinforced sections, the ACI code shear strength equations predict 10-30% lower capacity than the corresponding equations in the BS code.

• As the longitudinal steel reinforcement ratio increases, the ACI code prediction of the axial compressive strength of concentrically loaded cross-sections decreases from 10 to 25% below the corresponding strength predicted by the BS code.

• The load combinations involving dead load, live load and wind in the ACI code yield larger factored loads, by up to 20%, than the corresponding combinations in the BS code, especially for small wind-to-dead load ratios.

• Since the ACI 318 code predicts a little lower structural strength while at the same time slightly overestimates the factored load effect, compared to the BS 8110 code, the net effect results in a larger overall factor of safety. This translates to somewhat larger cross-sections and/or more steel reinforcement, and consequently higher construction costs, for members designed following the ACI 318 code over corresponding members sized based on the BS 8110 code.

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