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Comparision of Various Codes to Evaluate Design Capacity for Water Retaining Structure

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***Abstract:*— Calculation of Crack Width and satisfying the serviceability criteria along with checking for Limiting Moment and Shear plays a crucial role especially in the design of Water tank Container. This paper aims at comparing Service , Ultimate Moments and Hoop Tension for given reinforcement and its spacing corresponding to Container thickness, Clear cover, Grade of Concrete and Grade of Steel based on Crack Width, between IS 3370 (Part 2): 2009, BS 8110: 1997, Eurocode 2 1992-1 (2001), ACI 318. Rather it also fulfill the need of standardization for finding the Reinforcement required based on given Service and Ultimate Moments which will take care of Crack Width.**

***Index Terms* - Grade of Concrete and Steel, Clear cover, Container thickness, Ultimate and Service Moment.**

I. INTRODUCTION

Most of the codes are based on Limit State design concept with checking the serviceability condition. The checks are Strength parameters, Service Moment (Ms), Ultimate Moment (Mu), Limiting Shear (Vs) and Limiting Crack Width. To help in ease for design, some standardized design tables have been proposed for reinforcement and its spacing corresponding to the given service and ultimate moments for given container thickness, clear cover, grade of concrete and steel besides that a comparative study has been done between IS 3370 (Part 2): 2009 [1], BS 8110: 1997 [2], Eurocode 2 1992-1 (2001) [3], ACI 318 [4].

II. CRACK WIDTH CALCULATION AS PER ABOVE CODES

A. IS 3370 (Part 2): 2009

1) Service and Ultimate Moments

IS 3370 (Part 2): 2009 emphasizes three factors that decides the crack width. They are:

(a) The vicinity to the considered point of reinforcing bars transverse to cracks.

(b) The vicinity of neutral axis to the considered point.

(c) The average surface strain at the considered point.

It is recommended by IS 3370 (Part 2): 2009 that strain in the tension reinforcement is limited to 0.8 *fy/Es* and stress in concrete is limited to 0.45 *fcu*, and in no case it should exceed 0.3mm. The formula to predict the crack width is given as,

$$w = \frac{3 \times a_{cr} \times \varepsilon_m}{1 + 2\left(\frac{a_{cr} - c_{min}}{D - x}\right)} \quad (1)$$

where a_{cr} = distance from the considered point to the surface of the nearest longitudinal bar; ε_m = average strain at the level where the cracking is being considered; c_{min} = minimum cover to the tension steel; D = overall depth of the member; x = depth of neutral axis.

For cracked section, the formula for ε_m is given as:

$$\varepsilon_m = \varepsilon_1 - \varepsilon_2 \quad (2)$$

Where = strain at the level considered, and; = strain due to stiffening effect of concrete between cracks. 1 □ 2 □

$$\varepsilon_2 = \frac{b_t(D-x)(a'-x)}{3E_s A_s (d-x)} \quad (3)$$

For a limiting design surface crack width of 0.2mm and

$$\varepsilon_2 = \frac{1.5 b_t(D-x)(a'-x)}{3E_s A_s (d-x)} \quad (4)$$

For a limiting design surface crack width of 0.1mm

where b_t = width of the section at the centroid of the tension steel; a' = distance from the compression face to the point at which the crack width is being calculated.

After rearranging equation (1) for ε_m and ε_1 can be evaluated from equation (2) and from strain diagram of concrete stress block, by applying similar triangles we get stress at considered level f_s as:

$$f_s = \left(\frac{d-x}{D-x}\right)\varepsilon_1 E_s \quad (5)$$

The expression for Service Moment M_s is

$$M_s = f_s A_s Z \quad (6)$$

where Z = lever arm depth; By substituting equation (1), (2), (3), and (5) in (6) and rearranging for M_s as:

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$$M_s = \left(\frac{d-x}{D-x}\right)\left\{\frac{W\left[1+2\left(\frac{a_{cr}-c_{min}}{D-x}\right)\right]}{3a_{cr}}+\varepsilon_2\right\}E_s A_s\left[d-(x/3)\right] \qquad (7)$$

and the expression for Ultimate Moment Mu given in IS 456:
2000[5] as per Limit State Method is as follows:

$$M_u = 0.36 f_{ck} x_u b(d - 0.42 x_u) \qquad (8)$$

where fck = grade of concrete; xu = limiting neutral axis depth;
b = width of section.

2) Service and Ultimate Hoop Tension
As per IS 3370 (Part 2): 2009, the stiffening effect of Concrete under direct tension can be predicted from the formula as follows:

$$\varepsilon_2 = \frac{2b_t D}{3E_s A_s} \qquad (9)$$

and the Crack Width under direct tension can be predicted by
the formula as follows:

$$W = 3a_{cr}\varepsilon_m \qquad (10)$$

Now substituting equation (9) and (10) in (2) for 1 □ and there
by substituting value of 1 □ in equation (5) for fs we get:

$$f_s = \left(\frac{d-x}{D-x}\right)\left(\frac{W}{3a_{cr}}+\frac{2b_t D}{3E_s A_s}\right)E_s \qquad (11)$$

On the other hand, as we know that Service Tension Ts is calculate as:

$$T_s = f_s A_s \qquad (12)$$

After substituting equation (11) in (12) for Ts we get:

$$T_s = \left(\frac{d-x}{D-x}\right)\left(\frac{W}{3a_{cr}}+\frac{2b_t D}{3E_s A_s}\right)E_s A_s \qquad (13)$$

and the expression for Ultimate Tension Tu can be calculated
from the stress block parameters under Limit State Method
given in IS 456: 2000 as follows:

$$T_u = 0.87 f_y A_s \qquad (14)$$

B. BS 8110:1997

1) Service and Ultimate Moments

BS 8110: 1997 It's provisions are based on Beeby [6] empirical equations, and it emphasizes three factors that decide the crack width as stated in 2.1.
It is recommended by BS 8110: 1997 that strain in the tension reinforcement is limited to 0.8 fy/Es and stress in concrete is limited to 0.45 fcu, and in no case it should exceed 0.3mm. The formula to predict the crack width is given as,

$$w = \frac{3 \times a_{cr} \times \varepsilon_m}{1+2\left(\frac{a_{cr}-c_{min}}{h-x}\right)} \qquad (15)$$

where acr = distance from the considered point to the surface of the nearest longitudinal bar; εm = average strain at the level
where the cracking is being considered; cmin = minimum cover to the tension steel; h = overall depth of the member;
x = depth of neutral axis.
For cracked section, the formula for εm is given as:

$$\varepsilon_m = \varepsilon_1 - \varepsilon_2 \qquad (16)$$

Where 1 □ = strain at the level considered, and; 2 □ = strain due to stiffening effect of concrete between cracks.

$$\varepsilon_2 = \frac{b(h-x)(a'-x)}{3E_s A_s(d-x)} \qquad (17)$$

For a limiting design surface crack width of 0.2mm and

$$\varepsilon_2 = \frac{1.5b(h-x)(a'-x)}{3E_s A_s(d-x)} \qquad (18)$$

For a limiting design surface crack width of 0.1mm
where b = width of the section at the centroid of the tension steel; a' = distance from the compression face to the point at which the crack width is being calculated.
After rearranging equation (15) we get εm and 1 □ can be calculated from equation (16) and from strain diagram of concrete stress block, by applying similar triangles we get stress at considered level fs as:

$$f_s = \left(\frac{d-x}{h-x}\right)\varepsilon_1 E_s \qquad (19)$$

The expression for Service Moment Ms is

$$M_s = f_s A_s Z \qquad (20)$$

where Z = lever arm depth; By substituting equation (15), (16), (17), and (19) in (20) and rearranging for Ms as:

$$M_s = \left(\frac{d-x}{h-x}\right)\left\{\frac{W\left[1+2\left(\frac{a_{cr}-c}{h-x}\right)\right]}{3a_{cr}}+\varepsilon_2\right\}E_s A_s\left[d-(x/3)\right] \qquad (21)$$

and the expression for Ultimate Moment Mu given in BS 8110
as per Limit State Method is as follows:

$$M_u = 0.405 F_{cu} b x_u (d - 0.45 x_u) \qquad (22)$$

where Fcu = grade of concrete; xu = limiting neutral axis depth;
b = width of section.
The equations (21) and (22) are given by R.Cheng [7].

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2) Service and Ultimate Tension

As per BS 8110: 1997, the stiffening effect of Concrete under direct tension can be predicted from the formula as follows:

$$\varepsilon_2 = \frac{2b_t D}{3E_s A_s} \qquad (23)$$

and the Crack Width under direct tension can be predicted by the formula as follows:

$$W = 3a_{cr}\varepsilon_m \qquad (24)$$

Now substituting equation (23) and (24) in (16) for 1 and there by substituting value of 1 in equation (19) for fs we get:

$$f_s = \left(\frac{d-x}{h-x}\right)\left(\frac{W}{3a_{cr}} + \frac{2b_t h}{3E_s A_s}\right)E_s \qquad (25)$$

On the other hand, as we know that Service Tension Ts is calculated as:

$$T_s = f_s A_s \qquad (26)$$

After substituting equation (25) in (26) for Ts we get:

$$T_s = \left(\frac{d-x}{h-x}\right)\left(\frac{W}{3a_{cr}} + \frac{2b_t h}{3E_s A_s}\right)E_s A_s \qquad (27)$$

and the expression for Ultimate Tension Tu can be calculated from the stress block parameters under Limit State Method given in BS 8110: 1997 as follows:

$$T_u = 0.87 f_y A_s \qquad (28)$$

C. Eurocode 2 1992-1 (2001)

1) Service and Ultimate Moments

Eurocode2 recommends the following equation for calculating the flexural crack width.

$$W_k = S_{r,max}(\varepsilon_{sm} - \varepsilon_{cm}) \qquad (29)$$

where Wk = the design crack width, mm.

The mean tensile strain ( ) sm cm is given by:

$$(\varepsilon_{sm} - \varepsilon_{cm}) = \frac{\left(f_s - K_t\left(\frac{f_{cteff}(1+n\rho_{eff})}{\rho_{eff}}\right)\right)}{E_s} \geq 0.6\frac{f_s}{E_s} \qquad (30)$$

where sm is the mean strain in the reinforcement under the relevant combination of loads, accounting effect due to imposed deformations and tension stiffening; cm is the mean strain in concrete between cracks. Kt = factor expressing the duration of loading: Kt = 0.6 for short term loading and Kt = 0.4 for long term loading, fs = the stress in the tension reinforcement computed on the basis of a cracked section, n = the modular ratio, fcteff = the mean value of tensile strength of the concrete effective at the time when the cracks may first be expected to occur,

$$\rho_{eff} = \frac{A_s}{A_{ceff}} \qquad (31)$$

A ceff = effective tension area, is the area of concrete surrounding the tension reinforcement. r,max S = the maximum crack spacing, mm and the corresponding equation is,

$$S_{r,max} = 3.4c + 0.425k_1k_2\phi/\rho_{eff} \qquad (32)$$

where c = concrete clear cover, 1 k = coefficient that accounts the bond properties of the bonded reinforcement and equals to 0.8 for HYSD bars, and equals to 1.6 for mild steel bars, ϕ = bar diameter in mm; 2 k = coefficient that accounts for strain distribution and is 0.5 for sections subjected to pure bending and 1.0 for sections under pure axial tension. By substituting equation (30) in (29) and rearranging for fs we get:

$$f_s = k_t\left(\frac{f_{cteff}(1+n\rho_{eff})}{\rho_{eff}}\right) + \left(\frac{W_k * E_s}{S_{r,max}}\right) \qquad (33)$$

Substituting equation (33) in equation (20) for Ms we get:

$$M_s = \left(k_t\left(\frac{f_{cteff}(1+n\rho_{eff})}{\rho_{eff}}\right) + \left(\frac{W_k * E_s}{S_{r,max}}\right)\right)A_s(d - x/3) \qquad (34)$$

where d = effective depth; x = elastic neutral axis depth.

The expression for Mu given in Eurocode 2 is as follows:

$$M_u = 0.453 f_{ck} b(d-z)z \qquad (35)$$

where z = depth of lever arm = (d - 0.4xu); fck = grade of concrete; xu = limiting neutral axis depth; b = width of section.

2) Service and Ultimate Tension

As we know that Service Tension Ts is calculated as:

$$T_s = f_s A_s \qquad (36)$$

After substituting equation (33) in (36) for Ts we get:

$$T_s = \left(k_t\left(\frac{f_{cteff}(1+n\rho_{eff})}{\rho_{eff}}\right) + \left(\frac{W_k * E_s}{S_{r,max}}\right)\right)A_s \qquad (37)$$

and the Ultimate Tension Tu can be calculated from the stress block parameters under Limit State Method given in Eurocode 2 1992-1 (2001) as follows:

$$T_u = 0.87 f_y A_s \qquad (38)$$

D. ACI 318

1) Service and Ultimate Moment

Flexural crack control requirements in ACI were based on z-factor method which was developed by Gergely and Lutz [8]. The equation proposed by ACI 318-95 is as follows:

0.011 *10 mm, 3 3

$$W_{max} = 0.011\beta f_s \sqrt[3]{d_c A_o} * 10^{-3} \text{mm}, \quad (39)$$

where $\beta = \frac{h-x}{d-x} = 1.20$ in beams h = overall depth; d = effective depth; x = depth of neutral axis; A_o = the area of concrete surrounding each reinforcing bar = A_e/n_b, $A_e = 2d_c b$ the effective area of concrete in tension; nb = number of bars; dc = distance between center of bar and extreme tensioned fiber. ACI 318 limits the crack width to 0.4 mm and usage of fs = 0.67 fy for computation of service moment for above limited crack width. Rearranging equation (39) for fs and substituting in equation (20), we get Ms as follows:

$$M_s = \left(\frac{Z}{\sqrt[3]{2bd_c^2}} \right) A_S (d - x/3) \quad (40)$$

where, $Z = \frac{W_{max}}{0.011 \times \beta \times 10^{-3}}$.

The expression for Mu given by ACI 318 is as follows:

$$M_u = 0.85 f_{ck} x b (d - x_u/2) \quad (41)$$

where x_u = limiting neutral axis depth; f_{ck} = grade of concrete; b = width of section.

The formula for f_s can be evaluated form equation (40), and it is as follows:

$$f_s = \left(\frac{Z}{\sqrt[3]{2bd_c^2}} \right) \quad (42)$$

2) Service and Ultimate Tension

As we know that Service Tension T_s is calculated as:

$$T_s = f_s A_s \quad (43)$$

After substituting equation (42) in (43) for T_s we get:

$$T_s = \left(\frac{Z}{\sqrt[3]{2bd_c^2}} \right) A_s \quad (44)$$

stress block parameters under Limit State Method given in
ACI 318-95 as follows:

$$T_u = f_y A_s \quad (45)$$

III. COMPARISON BETWEEN CODES

Using the formulae that are discussed above, comparison has been carried out for Ultimate, Service moments Mu, Ms and Hoop Tension Ts, Tu. Tables have been prepared for selective common conditions. However to save the space only few tables are presented below. They are:

Grade of Concrete M30, Grade of Steel Fe415, Clear Cover CC 40mm, ϕ = Bar Diameter (mm).

Table 1 (a) Wall thickness t = 200mm, ϕ @ 100mm c/c
ϕ 8 10 12 16

	ϕ	8	10	12	16
IS 3370	M_s (KNm/m)	23	30	38	58
	T_s (KN/m)	161	191	225	301
	M_u (KNm/m)	27	41	56	90
	T_u (KN/m)	181	284	408	726
BS 8110	M_s (KNm/m)	23	30	39	59
	T_s (KN/m)	162	193	229	308
	M_u (KNm/m)	27	41	57	91
	T_u (KN/m)	181	284	408	726
EC 2	M_s (KNm/m)	23	30	38	58
	T_s (KN/m)	160	206	266	431
	M_u (KNm/m)	27	41	58	94
	T_u (KN/m)	181	284	408	726
ACI 318	M_s (KNm/m)	14	20	28	44
	T_s (KN/m)	93	141	196	323
	M_u (KNm/m)	32	48	68	113
	T_u (KN/m)	209	326	469	834

Table 1 (b) Wall thickness t = 200mm, ϕ @ 125mm c/c

	ϕ	8	10	12	16
IS 3370	M_s (KNm/m)	20	25	31	46
	T_s (KN/m)	142	162	186	240
	M_u (KNm/m)	22	33	46	75
	T_u (KN/m)	145	227	327	581
BS 8110	M_s (KNm/m)	20	25	32	47
	T_s (KN/m)	143	164	189	245
	M_u (KNm/m)	22	33	46	76
	T_u (KN/m)	145	227	327	581
EC 2	M_s (KNm/m)	21	25	31	47
	T_s (KN/m)	143	176	220	341
	M_u (KNm/m)	22	34	47	78
	T_u (KN/m)	145	227	327	581
ACI 318	M_s (KNm/m)	10	15	21	33
	T_s (KN/m)	70	105	147	243
	M_u (KNm/m)	25	39	55	93
	T_u (KN/m)	167	261	375	668

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Table 1 (c) Wall thickness t = 200mm, ϕ @ 150mm c/c

	ϕ	8	10	12	16
IS 3370	M_s (KNm/m)	17	22	27	39
	T_s (KN/m)	130	144	161	201
	M_u (KNm/m)	18	28	39	65
	T_u (KN/m)	121	189	272	484
BS 8110	M_s (KNm/m)	18	22	27	40
	T_s (KN/m)	130	146	163	205
	M_u (KNm/m)	18	28	39	65
	T_u (KN/m)	121	189	272	484
EC 2	M_s (KNm/m)	20	23	27	39
	T_s (KN/m)	132	158	191	285
	M_u (KNm/m)	18	28	40	66
	T_u (KN/m)	121	189	272	484
ACI 318	M_s (KNm/m)	8	12	17	27
	T_s (KN/m)	55	83	116	192
	M_u (KNm/m)	21	33	46	78
	T_u (KN/m)	139	217	313	556

Table 1 (d) Wall thickness t = 200mm, ϕ @ 175mm c/c

	ϕ	8	10	12	16
IS 3370	M_s (KNm/m)	16	19	24	34
	T_s (KN/m)	122	132	145	174
	M_u (KNm/m)	16	24	34	56
	T_u (KN/m)	104	162	233	415
BS 8110	M_s (KNm/m)	16	20	24	34
	T_s (KN/m)	122	133	146	177
	M_u (KNm/m)	16	24	34	57
	T_u (KN/m)	104	162	233	415
EC 2	M_s (KNm/m)	19	21	25	34
	T_s (KN/m)	125	146	173	248
	M_u (KNm/m)	16	24	34	58
	T_u (KN/m)	104	162	233	415
ACI 318	M_s (KNm/m)	7	10	14	22
	T_s (KN/m)	45	68	95	158
	M_u (KNm/m)	18	28	40	68
	T_u (KN/m)	119	186	268	477

Table 1 (e) Wall thickness t = 200mm, ϕ @ 200mm c/c

	ϕ	8	10	12	16
IS 3370	M_s (KNm/m)	15	18	21	30
	T_s (KN/m)	116	124	133	155
	M_u (KNm/m)	14	21	30	50
	T_u (KN/m)	91	142	204	363
BS 8110	M_s (KNm/m)	15	18	22	30
	T_s (KN/m)	117	125	135	158
	M_u (KNm/m)	14	21	30	50
	T_u (KN/m)	91	142	204	363
EC 2	M_s (KNm/m)	18	20	23	31
	T_s (KN/m)	121	138	160	221
	M_u (KNm/m)	14	21	30	51
	T_u (KN/m)	91	142	204	363
ACI 318	M_s (KNm/m)	6	8	11	19
	T_s (KN/m)	38	57	79	133
	M_u (KNm/m)	16	25	35	60
	T_u (KN/m)	104	163	235	417

IV. CONCLUSIONS

From the above study it is noticed that

(i). As the spacing between bar increases both Ms and Mu decreases.

(ii). Using of ACI 318 code gives conservative design results compared to other codes.

(iii). The Ms values of IS 3370, BS 8110 are almost same while when they are compared with the EC 2, the Ms values from EC 2 are on conservative side till the value of wall thickness (t) is 200mm. After that they are lower than that of IS 3370, BS 8110.

(iv). In some cases the Ms values are greater than Mu values those values cannot be used for design and alternative bar diameter and spacing be chosen as per the requirement.

(v). The similar tables can be prepared for various selective common conditions i.e; for different Grade of Concrete, Steel, Clear Cover, by using above mentioned formulae.

(vi). It is observed that with decrease in wall thickness and spacing, the Ms values are going lesser than the Mu values for IS 3370, BS 8110, EC 2 on the other hand there is no such difference is observed with ACI 318. On the other hand, Ts and Tu values are decreasing continuously.

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