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A Relative Comparison of Actions and Strength in Four Concrete Building Design Codes

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Summary

Concrete building design codes from USA, Britain, Egypt, and the Eurocodes are considered. Comparisons of the provisions for actions (loads), and for resistance(strength) of sections in flexure are carried out. Several parameters are considered including variable actions for residential buildings, offices, shops, and different material strengths. Issue and consequences of mixing actions from one code & resistance from another code are also discussed.

1. Introduction

Structural Design codes of different countries provide the engineers with data and procedures for design of the structural components. Differences, sometimes large differences, could be noticed between the codes in the data given for actions, in the provisions for evaluating resistance of sections, and also in other code requirements for durability, detailing,...The paper presents a quantitative comparison of four concrete building codes. Actions and resistances are evaluated and compared for several cases.

Scope of Work: The design codes and load codes considered are ACI 318-89 and ASCE 7-88 from USA, BS 8110 and BS 648/BS 6399 from Britain, EC1 and EC2 from European Community, and Egyptian code of practice for the design of reinforced concrete structures (ECOP 89) and code for Loads (ECOPL 93). The following parameters are considered in the study: *i)* Permanent actions (dead loads) and Variable actions of buildings (live loads), *ii)* Types of building occupancy for variable actions: residential, offices and shops, *iii)* Action effects: flexure and longitudinal force, *iv)* Structural elements: beams and axially loaded short columns (briefly), *v)* Limit states: ultimate limit state, *vi)* Steel yield strength f_{yk} = 360, 500 N/mm^2 and concrete cylinder strength f_{ck} = 25, 40 N/mm^2.

2. Basis for Comparison of the Four Considered Codes

Consider a beam in a typical one way slab construction, e.g. beam *b1* shown in *Fig. 1.* If this beam is designed, for example according to the ACI code, it is required that at failure (assuming b_1 is a singly reinforced beam):

$$(1.4w_D + 1.7w_L)\ \frac{Bl^2}{8}\ \leq\ \phi\ \rho\ f_y(1 - 0.59\frac{\rho\ f_y}{f'_c})\ bd^2$$

$$(1.4w_D + 1.7w_L)\ C_1\ \leq\ \mu\ bd^2$$

$$bd^2\ \geq\ \frac{(1.4w_D + 1.7w_L)}{\mu}\ C_1 \qquad (1)$$

In equation 1, C_1 is a function of the structural system, and the area supported by the beam. C_1 does not, in most cases, differ from one code to the other. Numerator of Equ. (1) is a function of of the live load & the load factors given in the codes, and also of weight of structural and non-structural elements. Denominator of Equ. (1) is a function (f'_c, f_y, ρ), which are selected by the designer, and a function of the resistance model given in the code (stress-strain relations, limit strain, stress block shape, partial safety factors for materials γ_m). Equations similar to Equ.(1) could be written for different codes and for different load effects.

Evaluating the numerator of Equ. (1), a comparison of the ultimate design loads in different codes can be done. This is described in Sec. 3, & in Tables 1,2,3. Evaluating the denominator of Equ. (1), a quantitative comparison of the ultimate moment of resistance, as given by the different codes, can be done. Details are given in Sec. 4, and in Table 4. Above comparisons are useful, but they are not sufficient. Comparison of codes should include both action and resistance. This could be achieved using Equ. (1) as described below.

Consider two codes: code 1, and code 2. Using Equ. (1), bd^2 is evaluated for both codes (in terms of C_1). Then, the ratio of bd^2 for code 1 to bd^2 for code 2 is evaluated (C_1 is eliminated). If this ratio is larger than 1, then code 1 is more conservative (or less economic) than code 2, and vice versa. Repeating above process for several cases could give an idea on the economy of concrete structures as designed according to different codes. Examples are given in Sec. 5 and Table 6.

3. Actions in The Four Considered Codes

Table 1 presents some values of variable actions (LL) specified for different types of building occupancy. Notice, for example, large differences in live load intensities given for balconies, large differences for corridors in residential bldgs., & small differences for stair loads in shops.

Table 2 presents above values (LL) combined with permanent actions (DL), each multiplied by relevant load factor for ultimate limit state, i.e., Table 2 presents the evaluation of numerator of Equation 2. Following assumptions are made for evaluating items in Table 2: *i)* DL, LL are applied to the same area, *ii)* The lower value of DL intensities (3 kN/m^2) correspond to DL in thin slab or void slab construction plus the flooring weight, and the higher value (7 kN/m^2) correspond to dead loads in thick slab constructions plus the flooring weight.

Use	Code	Floors kN/m²	Corridors kN/m²	Stairs kN/m²	Balconies kN/m²
Residential	ACI 318-89	1.9	4.8	4.8	4.8
	EC2	2.0	2.0	3.0	4.0
	BS 8110	1.5	4.0	1.5	1.5 [b]
	ECOP 89	2.0	2.0 ⊕	3.0	3.0
Offices	ACI 318-89	2.4	4.8	4.8	4.8
	EC2	3.0	3.0	3.0	3.0
	BS 8110	2.5	4.0	4.0	2.5 [b]
	ECOP 89	2.5	2.5 ⊕	4.0	4.0
Shops	ACI 318-89	4.8	4.8	4.8	4.8
	EC2	5.0	5.0	5.0	5.0
	BS 8110	4.0	4.0	4.0	4.0 [b]
	ECOP 89	5.0 [a]	5.0 [a]	5.0 [a]	5.0 [a]

a- The variable action intensity for warehouses & stores is given by ≥ 10.0 *kN/m²* (according to the stored materials).
b- Imposed Load to be same as that on floor to which access is given.
⊕ This value is assumed to be same as that of floors.

Table 1. Values of Variable Action Intensities for Different Types of Building's Occupancy in Four Different Codes

Use	Dead Load kN/m²	ACI / EC2	EC2 / EC2	BS 8110 / EC2	ECOP 89 / EC2	EC2 Value kN/m²
Residential (Floors)		*0.95*	*1.0*	*0.75*	*1.00*	***2.00***
	3.00	1.05 **	1.0	0.94	1.06	7.05 ⊕
	4.00	1.05	1.0	0.95	1.07	8.40
	7.00	1.05	1.0	0.98	1.08	12.45
Residential (Balconies)		*1.20*	*1.0*	*0.375*	*0.75*	***4.00***
	3.00	1.23	1.0	0.66	0.90	10.05
	4.00	1.21	1.0	0.70	0.91	11.40
	7.00	1.16	1.0	0.79	0.97	15.45
Offices (Floors)		*0.80*	*1.0*	*0.833*	*0.833*	***3.00***
	3.00	0.97	1.0	0.96	0.96	8.55
	4.00	0.98	1.0	0.97	0.97	9.90
	7.00	0.99	1.0	0.99	1.02	13.95

** $1.05 = \dfrac{1.4\,D_{ACI} + 1.7\,L_{ACI}}{1.35\,D_{EC2} + 1.5\,L_{EC2}}$ ⊕ $7.05 = 1.35\,D_{EC2} + 1.5\,L_{EC2}$

Notes: 1- The values written in bold italic font represent the Variable Action intensity according to EC2, Values are taken from *Table 1.*
2- The values written in italic font represent relative Variable Action intensity with respect to EC2.
3- Columns 3,4,5,6 give relative values with respect to EC2

Table 2. Comparison of Ultimate Loads for Different Types of Building's Occupancy in Four Different Codes

			Dead Loads D		Live Loads L		Wind Loads W	
ACI 318-89	Case	Loads Considered	Max*	Min**	Max*	Min**	Max*	Min**
	1	D, L	1.4	0.9!	1.7	0	-	-
	2	D, L, W	0.75x1.4	0.75x1.4!	0.75x1.7	0.75x1.4!	0.75x1.7	0.75x1.7!
	3	D, W	0.75x1.4	0.9	-	-	0.75x1.7	1.3
	* Loads increase load effect under consideration							
	** Loads decrease load effect under consideration							
	! This value is assumed by the authors							

			Permanent Loads G_K		Variable Imposed Loads Q_K		Wind Loads W_K
EC2	Case	Loads Considered	Adverse	Beneficial	Adverse	Beneficial	
	1	G_K, Q_K	1.35	1.00	1.50	0	-
	2	G_K, Q_K, W_K	1.35	1.00	1.35	0	1.35
	3	G_K, W_K	1.35	1.00	-	-	1.50
	(Simplified Combination Rules With Only One Variable Action)						

			Dead Loads G_K		Live Loads Q_K		Wind Loads W_K
BS 8110	Case	Loads Considered	Adverse	Beneficial	Adverse	Beneficial	
	1	G_K, Q_K	1.4	1.0	1.6	0	-
	2	G_K, Q_K, W_K	1.2	1.2	1.2	1.2	1.2
	3	G_K, W_K	1.4	1.0	-	-	1.4

			Dead Loads D		Live Loads L		Wind Loads W
ECOP 89	Case	Loads Considered	Adverse	Beneficial	Adverse	Beneficial	
	1	D, L *	1.4	0.9	1.6	0	-
	2	D, L, W	0.8 x 1.4	0.8 x 1.4	0.8 x 1.6	0.8 x 1.6	0.8 x 1.6
	3	D, W	1.4	0.9	-	-	1.3
	* For cases when live loads does not exceed 0.75 the dead loads, the ultimate load U becomes, $U = 1.5\,(D + L)$						

Table 3. Partial Safety Factors for Actions at The Ultimate Limit State According to Four Different Codes.

Table 2 gives examples of values of the ultimate loads (DL, LL) for the codes considered in this study, evaluated with respect to ultimate load of EC2. The last column gives the values of ultimate loads for the EC2 in kN/m^2. The following general observations could be made concerning cases considered: *i)* ACI gives higher values of ult. loads for floors and balconies of residential buildings, and values near the average for office floors, *ii)* BS code gives lower values of ultimate loads when compared with the other three codes. This may be due to the lower values of variable action intensities in this code, *iii)* The differences between ultimate loads in the four codes decrease, in general, with the increase of the value of DL.

4. Resistance of Reinforced Concrete Sections in Flexure and Axial Loads

Flexural Resistance: The ultimate moments of resistance for a singly reinforced sections are given in Table 4. Parameters considered are shown in the table. Concerning characteristic concrete cylinder strength, and also steel strength, it should be mentioned that the used values may not correspond to the specific grades of the codes considered. However, since our interest here is to compare ultimate moments of resistance according to provisions of different codes, the same material strength should be used. It should be mentioned also that most information in ECOP 89 are for concrete cube strength up to f_{cu} = 30 N/mm². For the sake of the comparative study, used values of concrete strength used in the study are assumed to be applicable. Table 4 presents the relative values of the ultimate moment of resistance with respect to EC2. The last column gives the values of M_u for EC2 in terms of bd^2 (units of *N,mm*). The following observations could be made:

f_{ck} *N/mm²*	f_{yk} *N/mm²*	ρ %	Values Relative to EC2 Code				EC2 Value
			$\frac{ACI}{EC2}$	$\frac{EC2}{EC2}$	$\frac{BS\ 8110}{EC2}$	$\frac{ECOP\ 89}{EC2}$	bd^2 *N/mm²*
25	360	0.5	1.05	1.0	1.00	1.00	1.48
25	360	1.0	1.06	1.0	1.00	1.00	2.78
25	360	1.5	1.08	1.0	1.00	1.00	3.92
25	500	0.5	1.05	1.0	1.00	1.00	2.01
25	500	1.0	1.08	1.0	1.00	1.00	3.68
25	500	2.0	1.14	1.0	1.00	1.00	6.03
40	360	0.5	1.04	1.0	1.00	1.00	1.51
40	360	1.0	1.05	1.0	1.00	1.00	2.91
40	360	2.0	1.07	1.0	1.00	1.00	5.40
40	500	0.5	1.05	1.0	1.00	1.00	2.07
40	500	1.0	1.06	1.0	1.00	1.00	3.93
40	500	2.0	1.09	1.0	1.00	1.00	7.03

Notes: 1 - The values shown in the last column should be multiplied by bd^2 in (mm) to obtain the ultimate moment of resistance of the sec. in (N.mm).
2 - Columns 4,5,6,7 give relative values with respect to EC2.
3 - The above values are derived for under reinforced sections ($\rho < \rho_{balanced}$).

Table 4. Comparison of Ultimate Moment of Resistance of Singly Reinforced Concrete Sections in Four Codes

i) The ultimate moments of resistance are observed to be 4% to 14% higher for the ACI than for the EC2, BS 8110, ECOP 89. This difference increases slightly with the increase of (ρ).
ii) The values of ultimate moment of resistance of singly under reinforced concrete sections, M_u, are the same for EC2, BS 8110, ECOP 89. This is because, for the cases considered, the three codes use the same equivalent concrete block, & the same material partial safety factors.

Axial Resistance: Table 5 presents a comparison of the ultimate axial strength of columns, P_u. The columns are considered to be short, effect of buckling neglected. For the design of axially loaded short columns according to EC2, the following quotation is taken from Ref. 4, pp. 247. " For EC2 code, to avoid the necessity of considering slenderness effects, limit the story height to least lateral dimension of the columns to 12. Allow for bending effects by increasing the axial load by 25 to 50 percent. Working in terms of axial load only, the design ultimate load capacity of section is: $N_{ud} = \alpha \cdot f_{cd} \cdot A_c + f_{yd} \cdot A_s$, N_{ud} = ult. value of applied axial force, with: $\alpha = 0.85$, $f_{cd} = f_{ck}/1.5$, $f_{yd} = f_{yk}/1.15$ $N_{ud} = 0.57 \cdot f_{ck} \cdot A_c + 0.87 \cdot f_{yk} \cdot A_s$ "

f_{ck} *N/mm²*	f_{yk} *N/mm²*	ρ %	Values Relative to EC2 Code				EC2 Value
			$\frac{ACI}{EC2}$	$\frac{EC2}{EC2}$	$\frac{BS\ 8110}{EC2}$	$\frac{ECOP\ 89}{EC2}$	bd *N/mm²*
25	500	1.0	0.78	1.0	0.87	0.77	18.60
25	500	3.0	0.73	1.0	0.87	0.77	27.30
40	500	1.0	0.80	1.0	0.87	0.77	27.15
40	500	3.0	0.75	1.0	0.87	0.77	35.85

Notes: 1- The values shown in the last column should be multiplied by the cross section dim. in (mm) to obtain the ultimate strength of column (Newton).
2- Columns 4,5,6,7 give relative values with respect to EC2.

Table 5. Comparison of Ultimate Strength of Axially Loaded Short Columns in Four Codes

5. Comparison of Codes Considering both Actions and Resistance

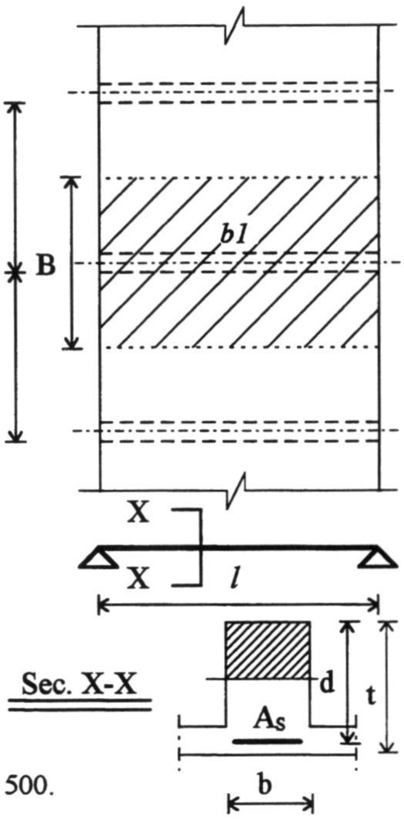
Section 3 presented a comparison between variable actions, and variable actions combined with permanent actions. Section 4 presented a comparison between ultimate resistance of concrete sections. These comparisons could be useful. They showed differences and similarities between codes. However, a better comparison between codes must involve both actions and resistance. For that purpose, three examples are given in the following.

Figure 1: shows the ultimate load effect and the ultimate section resistance of a singly reinforced beam. Data on dimensions & material properties are shown in figure. It is noted that beam dimensions of (t=450mm, b=200mm) satisfy the requirements of ACI, EC2, and BS codes, however they are unsafe for design using ECOP. This could be attributed ,partly, to the fact that the code uses a relatively higher partial safety factor for loads, equal to 1.5 for both DL & LL, when the value of the variable action does not exceed 0.75 the value of the DL.

Figure 2: The left four columns of Fig. 2 show the quantities of reinforcement needed for a singly reinforced beam, as computed according to the four codes considered in the study. Beam dimensions are t=450mm, b=200mm, f_{yk} = 500 N/mm², f_{ck} = 25N/mm².

Data For The Design Example:

- ⇨ Beam (*b1*) in a Residential Building floor.
- ⇨ Assume (*b1*) is a simple beam, $l > 2B$.
- ⇨ Assume (*b1*) is an inverted beam (rect. sec.).
- ⇨ Permanent Action = 7 kN/m^2 (from beam & slab).
- ⇨ $f_{ck} = 25\ N/mm^2$ ⇨ $f_{yk} = 500\ N/mm^2$ ⇨ $\rho = 1\ \%$
- ⇨ $B = 2.7\ m$ ⇨ $l = 5.5\ m$
- ⇨ $b = 200\ mm$ ⇨ $t = 450\ mm$ (except for ECOP)**



Summary of Results:

Code	Ult. Sec. Resistance *kN.m*	Ult. Action Effect *kN.m*
ACI 318-89	140.03	133.03
EC2	129.57	127.11
BS 8110	129.57	124.55
ECOP 89*	129.57	137.83
ECOP 89**	162.25	137.83

* Sec. does not satisfy ECOP. ** Increase sec. dim. to 200 X 500.

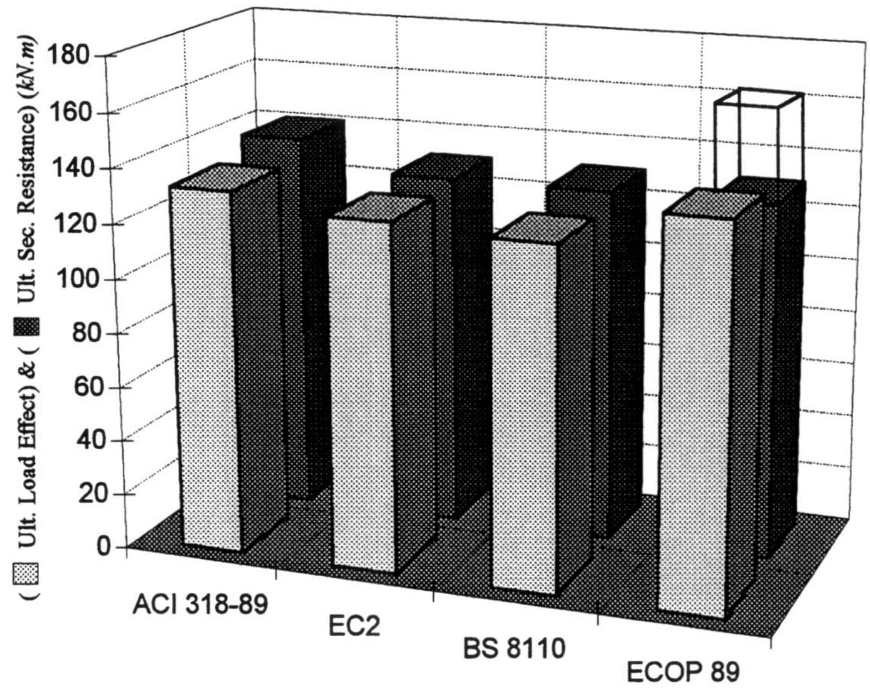


Fig. 1. Example to Show The Relation Between Ultimate Action Effect and Ultimate Section Resistance in Four Different International Codes.

Use	Materials N/mm^2	Permanent Load kN/m^2	ρ %	ACI / EC2	EC2 / EC2	BS 8110 / EC2	ECOP 89 / EC2
Residential	$f_{ck} = 25$	3	0.5	1.004	1.0	0.936*	1.064**
(Floors)	$f_{yk} = 360$	3	1.5	0.971	1.0	0.936	1.064
		7	0.5	0.997	1.0	0.980	1.084
		7	1.5	0.964	1.0	0.980	1.084
	$f_{ck} = 25$	3	0.5	0.998	1.0	0.936	1.064
	$f_{yk} = 500$	3	1.5	0.949	1.0	0.936	1.064
		7	0.5	0.991	1.0	0.980	1.084
		7	1.5	0.942	1.0	0.980	1.084
Offices	$f_{ck} = 40$	3	0.5	0.928	1.0	0.959	0.965
(Floors)	$f_{yk} = 360$	3	1.5	0.910	1.0	0.959	0.965
		7	0.5	0.953	1.0	0.989	1.022
		7	1.5	0.935	1.0	0.989	1.022
	$f_{ck} = 40$	3	0.5	0.925	1.0	0.959	0.959
	$f_{yk} = 500$	3	1.5	0.899	1.0	0.959	0.959
		7	0.5	0.950	1.0	0.989	1.022
		7	1.5	0.924	1.0	0.989	1.022

Note: *:it is assumed that* $f_{cu}\,(BS) = f_{cu}\,(ECOP) = 1.25\,f_{ck}\,(EC2) = 1.25\,f'_c\,(ACI)$

Examples: $* \; 0.936 = \dfrac{bd^2 \text{ (for BS 8110 Code)}}{bd^2 \text{ (for EC2 Code)}}$ $\quad ** \; 1.064 = \dfrac{bd^2 \text{ (for ECOP 89 Code)}}{bd^2 \text{ (for EC2 Code)}}$

The values of bd^2 for different codes are as follows:

ACI CODE : $bd^2 = \dfrac{(1.4D + 1.7L)\,Bl^2/8}{\phi\,\rho\,f_y\,(1 - 0.59\rho\,f_y/f'_c)}$

EC2 CODE : $bd^2 = \dfrac{(1.35G_K + 1.5Q_K)\,Bl^2/8}{0.87\,\rho\,f_{yk}\,(1 - 0.7787\rho\,f_{yk}/f_{ck})}$

BS 8110 CODE : $bd^2 = \dfrac{(1.4G_K + 1.6Q_K)\,Bl^2/8}{0.87\,\rho\,f_y\,(1 - 0.623\rho\,f_y/f_{cu})}$

ECOP 89 CODE :case 1, $L > 0.75D$, $bd^2 = \dfrac{(1.4D + 1.6L)\,Bl^2/8}{0.87\,\rho\,f_y\,(1 - 0.623\rho\,f_y/f_{cu})}$

case 2, $L \le 0.75D$, $bd^2 = \dfrac{1.5\,(D + L)\,Bl^2/8}{0.87\,\rho\,f_y\,(1 - 0.623\rho\,f_y/f_{cu})}$

Table 6. Comparison of The Relative Values of (bd^2) for Singly Under Reinforced Concrete Sections according to Four Different Concrete Codes.

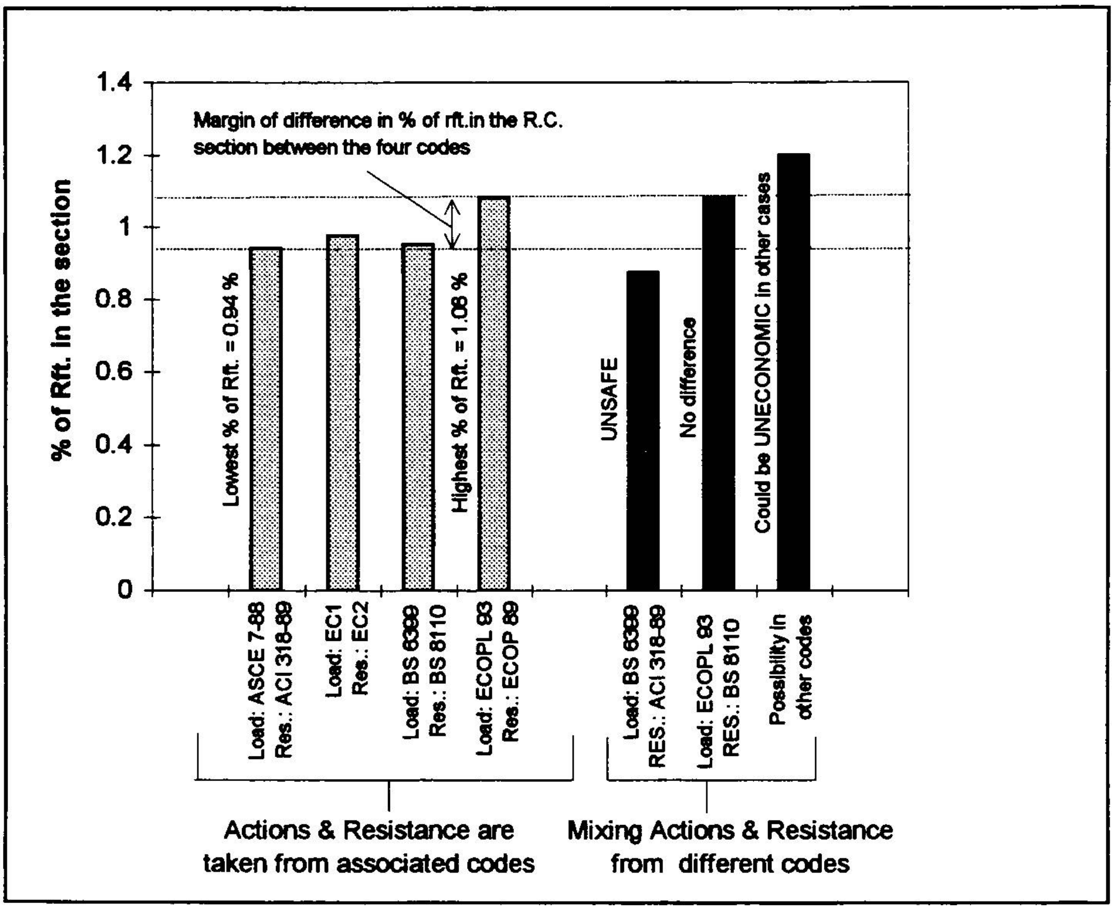


Fig. 2. Comparison of the Reinforcement Ratio [%] for a Singly Reinforced Beam Section in Flexure Calculated by Associated Codes & Mixed Codes

<u>*Table 6:*</u> In sec. 2, it was shown that evaluating bd^2 for different codes using Equ. (1), could be a measure of the economy of concrete structures designed according to these codes. Table 6 gives the relative values of (bd^2) of ACI 318-89, BS 8110, ECOP 89 with respect to EC2 for singly under reinforced concrete rectangular sections. Parameters considered are given in Table 6. It is noted that two intensities are considered for permanent actions to represent floors with different thickness, and also two types of building occupancy are considered. As an example concerning Table 6, (ECOP 89/EC2) = 1.064. This means that (bd^2 according to ECOP) = 1.064 (bd^2 according to EC2), i.e., for this case considered in Table 6, and considering the values of variable actions, the load factors, and the resistance models of the four codes, a concrete section designed according to Egyptian code requires slightly more materials than Eurocode, in the ratio 1.064 : 1.

6. Consequences of Mixing Design Codes

Mixing codes, i.e. using actions from one code and resistances from another code, is illegal. However, in some instances or in some regions which do not have their own codes or specifications, the practice of mixing codes is followed. Not only this is illegal, but it could be unsafe or uneconomic as shown in the last three columns of Fig. 2. For example, when using the ultimate loads from BS code and calculating the ultimate section resistance using ACI code, a lower steel reinforcement value is obtained. This structure could be unsafe.

7. Conclusions

Four concrete building design codes, and the corresponding codes for actions are considered. For the cases considered in the paper, the following conclusions can be made:
Actions: (1) Concerning variable actions, large differences in the variable actions intensities are observed in some cases, Table 1. (2) When variable actions are combined with permanent actions, the difference is still observed. However, the difference decreases with the increase of permanent action to variable action ratio, Table 2. (3) The ACI code gives higher values of ult. loads when compared with the other three codes. The EC code gives values of ult. loads near the average of the codes considered. The BS code gives lower values of ultimate loads when compared with the other three codes.
Resistances: (4) The ultimate moments of resistance are to some extent higher for the ACI than for the EC2, BS 8110, ECOP 89 codes. This difference increases slightly with the increase of steel content, Table 4. (5) The values of the ultimate moment of resistance of singly under reinforced concrete sections, M_u, are the same for EC2, BS 8110, ECOP 89.
Actions and resistances: (6) It is interesting to note that, in some cases, the ACI code gives higher ultimate action effects & higher ultimate section resistance than the EC2 & BS codes, however, it gives lower values of reinforcement, Fig. 2. (7) Beams designed by ACI and BS codes (Table 6) could be slightly more economic than those designed by EC2 and ECOP. (8) Using actions from one code & resistances from another code could lead to unsafe design.

8 Acknowledgment

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