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Safety Index Evaluation and Calibration of Load and Resistance Factors for Concrete Beams Under the Simultaneous Effects of Bending, Shear and Torsion

Amir Azhari
Department of Civil Engineering, Safadasht Branch, Islamic Azad University, Safadasht, Iran
A.azhari2017@gmail.com

Mohammad Reza Mesbahi
Department of Civil Engineering, Safadasht Branch, Islamic Azad University, Safadasht, Iran
Mesb[illegible]mail.com

***Abstract*—The conventional approach for designing reinforced concrete members is based on load and resistance factors. In spite of the fact that, the load and resistance parameters are random variables, constant values are designated to them during the design. However, accounting these factors as constants, will ultimately lead to unsafe and uneconomical designs. Safe designs of structures require the appropriate recognition of parameters and their uncertainties. This may be achieved by clarifying the effective design parameters and applying risk-based design methods. The main purpose of this paper is the reliability-based design of reinforcement concrete beams under the simultaneous effects of bending, shear and torsion. For this pu[illegible] computer program is developed, and the most usual secti[illegible] selected for studying. Rectangular sections with tension re[illegible] (singly reinforced), rectangular sections with tension a[illegible] compression rebars (doubly reinforced) and T-shape sections are designed based on probabilistic methods. An appr[illegible]ate tool for reliability calculations is selected based on th[illegible] cons of different methods. Evaluation of load and r[illegible]ance [illegible]rs for all mentioned beams is conducted. The steel [illegible]ges und[illegible] safety levels are determined. Hence, a me[illegible] the and fully probabilistic design of concrete beams [illegible]ed.**

Keywords-reinforced concrete be[illegible] reliability-based[illegible]; monte-carlo simulation; safety factor[illegible]d and resistance facto[illegible]

I. 1. IN[illegible]DUCT[illegible]

Using new designing methods based on [illegible]ility is a relatively old issue in ci[illegible] engineering [1] and a lot of researches on reliability [illegible]ed design have been conducted because the existing unc[illegible]inties in designing parameters and the use of constants in [illegible]ulation sometimes overshadow the design. So, using relia[illegible]ds based [illegible] the limit state governing the problem a[illegible]ing att[illegible]on to statistical parameters for each designing v[illegible] as mean, standard deviation and st[illegible]istribution [illegible] various regulations of designing [illegible] bee[illegible]ollowed in various countries. For example, in [illegible] the she[illegible] for[illegible]nforced concrete for a reinforced [illegible] be[illegible] regulations using a new reliability meth[illegible]culated. It has been indicated that various factors are [illegible] in the failure of concrete beam including the ratio of the [illegible]ngth over the effective depth, the [illegible]o of [illegible]inal steel, support conditions, loading conditions, and the [illegible] of materials. In (3), authors investigated the reliability of a concrete beam. The studied beam was designed under the effect of shear-bending-torsion. The failure level for three states of shear, bending, and torsion was considered [illegible]ording to the first order reliability method (FORM) and i[illegible]cated the fact that the safety index is [illegible]endent to [illegible] rate of live load, the rate of effective p[illegible]m strength as well as the uncertainty of the mode[illegible].

In [5], authors studied risk management in the reliability [illegible]ncrete infrastructures. In [6], authors investigated th[illegible]ity indices in beams and columns obtained for ACI-[illegible] regulation and the designed structures. In [7], authors studied the punching shear using the reliability method in a flat [illegible]b. In [8], a research in order to obtain the reliability index to [illegible] shear and reinforcement of bridges concrete was carried out. In [9], authors studied the reliability of a concrete bridge in which the intended beam was under the effect of moment and shear forces. In [10], the concrete safety index was investigated with regard to uncertainty parameters in various material. In [11], Greek seismic regulations were investigated focusing at the calibration of the regulations for the beam-column and beam members. In [12], authors studied the impact of the calibration of regulations and the theory of probability in designing concrete bridges performance.

In accordance with the recommendations made in [4] and other statistical studies carried out by researchers such as [13, 14], the safety index for dead load + live load is 3 for bending and 2 for shear and torsion that in the present study the interval of the safety index to the proposed value is studied. The aim of this study is to investigate the safety index of Iranian concrete regulations for three limit states of shear, bending and torsion and also for the combination of the above limit states. The present study, suggesting the limit relations, has investigated the limit functions of regulation and has calculated the safety level and coefficients for all proposed states.

According to these studies, in the present paper after determining the factors of uncertainty in a beam affected by torsion and based on effective limit functions in designing, the safety level of Iranian concrete regulations has been estimated using the Monte-Carlo method. To achieve this goal, the existing parameters of uncertainty have been recognized and its random production method is with a high number of about 1500000 and is based on statistical parameters such as mean, standard deviation and statistical distributions. Then, various limit states such as shear, torsion and bending have been considered and the safety level and the factors addressed in the regulations have been estimated.

II. Designing of Concrete Beams under Bending, Shear and Torsion Conditions

In order to calculate the safety index, we should calculate the limiter functions which show the structural efforts. The relations of bending calculating, shear and torsional efforts are presented in the following. The resistant moment of the section is given in (1), the shear force of the section in (2) and the torsion moment of the section in (3).

$$M_r = A_s f_y \left(d - \frac{A_s f_y}{1.7 f_c b d}\right) \quad (1)$$

$$V_r = \underbrace{0.2\phi_c b_w d \sqrt{f_c}}_{V_c} + \underbrace{\phi_s f_y A_v \frac{d}{s}}_{V_s} \quad (2)$$

$$T_r = 2\phi_s A_0 A_t \frac{f_y}{s} \quad (3)$$

In (1) to (3), M_r is the section moment of resistan[illegible] the shear moment of resistance and T_r is the torsional m[illegible] of resistance. Also, the parameters of A_s, f_y, f_c, b and d ar[illegible] depth of section, width of section, the concrete compressi[illegible] strength, tensile strength of the steel used and the amount o[illegible] steel required in the section, respectively. U[illegible] (1) to (3) separately for the states of shear, bending an[illegible] sed on forces applied on the sections, we have ca[illegible] ted the [illegible] minal values of the used steel with regulatio[illegible] 15]. In [illegible] bending design in all sections, the compres[illegible] as used. In the case of L-shape and T-shape[illegible] ctions, [illegible] roposed equations have been used by regula[illegible] s to obtain t[illegible] ion moment of resistance, and all use[illegible] uations are availa[illegible] n [15]. For shear and torsional state[illegible] am, the full sections of the beam (L, T and rectangular [illegible] pe[illegible] been considered. The factors considered in the [illegible] crete re[illegible] ns of Iran to increase the load factor and re[illegible] ce the resistan[illegible] designing are γ_D=1.25, γ_L=1.50 in li[illegible] tate for the dead loa[illegible] and live load respectively. As well [illegible] the reduction factors of steel and concrete strengths in de[illegible] ing sta[illegible] at limit state are $\varnothing_S$=0.85 and 0.60 respectively[illegible] e nee[illegible] statistic[illegible] information to analyze the reliability a[illegible] n Table [illegible]

III. Formul[illegible] of the Li[illegible] ion and Safety Index

For desig[illegible] all po[illegible] ilities of concrete beams under the simultaneou[illegible] rts o[illegible] r and torsion, the limit functions must [illegible] llowing conditions:

$$\begin{aligned} M_r &\le M_s \\ V_r &\le V_s \\ T_r &\le T_s \end{aligned} \quad (4)$$

In (4), the limit value[illegible] e forces that t[illegible] eam can tolerate. To estimate the safety i[illegible] first the amou[illegible] f steel required of section for three ment[illegible] forces is c[illegible] ulated and then using Hasofer-Lind [illegible] uation [[illegible] afety[illegible] dex is calculated according to (5).

$$\beta = \frac{\mu \ldots \mu_s}{\sqrt{\ldots^2}} \quad (5)$$

In this s[illegible] dy, th[illegible] index [illegible] tudied for different limit states in th[illegible] oncrete bea[illegible] th[illegible] ferent aspects using Monte Carlo te[illegible] que.

TA[illegible] I. [illegible] TISTICAL PROFILE OF THE PARAMETERS USED IN THE RES[illegible] CH FOR DE[illegible] THE SECTIONS OF REINFORCED CONCRETE (13-14)

Random variable	No[illegible] l value	Density Function	Mean	Standard deviation
f'_c (MPa)	21	Normal	19.3	0.18
f_y (MPa)	420	Normal	317	0.12
[illegible]	b h d	Normal	b h d	b/10 h/17 d/15
Area (mm^2)	A_s A_v A_t	Normal	A_s A_v A_t	0.03 0.03 0.03
Loading	D L	Normal Gamble	1.05D	0.1 0.40-0.25

Safety level of shear-torsion

Based on the previous studies, by limiting the equation (6) to a specified value, the combination of simultaneous effect of shear-torsion can be achieved in various sections of concrete.

$$\frac{V_r}{b_w d} + \frac{2T_u (b_w + d)}{(b_w d)^2} < 0.25\phi_c f_c \quad (6)$$

The safety level estimation of Iranian concrete regulations for shear and torsion is as follows: The amount of the shear steel is calculated according to the considered section and also (2). The calculating method is such that by assuming the certain amount of the dead load and placing the parameter ratio=(1-t)/t and changing the value of t from 0.4 to 1, the amount of live load gets calculated. The amount of shear load is obtained from adding the live load to the dead load and finally, with respect to (2) the required amount of shear steel is obtained. Applying the value of the moments acting on the beam (the moment of dead load + the moment of live load) and (3), the required torsional steel is calculated. The method of calculating the total moments exerted on the beam is similar to those of shear state and is practical by considering the proposed ratio in [3] for the amount of t. The limiting function considered for solve the problem by take the formulas presented in regulations for shear, torsion and the combination of shear and torsion is as in (7) to (9), respectively.

$$G=\frac{v_r}{b_w d}-\frac{v_s}{b_w d} \quad (7)$$

$$G=\frac{2T_r(b_w+d)}{(b_w d)^2}-\frac{2T_s(b_w+d)}{(b_w d)^2} \quad (8)$$

$$G=\left(\frac{v_r}{b_w d}+\frac{2T_u(b_w+d)}{(b_w d)^2}\right)-\left(\frac{v_s}{b_w d}+\frac{2T_s(b_w+d)}{(b_w d)^2}\right) \quad (9)$$

In the above equations, the index S is the load and moment exerted on the section (demand), r is the resistance level of the section (capacity) against acting loads. In sections 3-2 to 6-2, different levels of regulations are presented for various combinations of forces.

B. *The safety level of bending-torsion*

To investigate the safety level of Iranian regulations, the amount of shear and bending steel is calculated using (1) to (3). After calculating the amount of the moment of resistance exerted on the section and the amount of the applied loads, a limiting function such as in (10) and (11) is considered.

$$M_r=A_s f_y\left(d-\frac{A_s f_y}{1.7 f_c bd}\right)-M_s \quad (10)$$

$$G=\left(\frac{M_r c}{I}+\frac{2T_r(b_w+d)}{(b_w d)^2}\right)-\left(\frac{M_s c}{I}+\frac{2T_s(b_w+d)}{(b_w d)^2}\right) \quad (11)$$

In the equations above, the effects resulted from the loads (live+dead) is shown with index S, and the resistance [illegible] the section against the exerted loads according [illegible] characteristics of the constructed section is shown by index [illegible]

C. *The safety level of bending-shear*

Previously the amount of the require[illegible] been calculated. Also, the amount of the forces a[illegible]g on t[illegible]ection and the strength of the section has bee[illegible]btained [illegible] modes of shear, torsion and bending. Fo[illegible] bending and shear, the following limiti[illegible]ed.

$$G=\left(\frac{v_r}{b_w d}+\frac{M_r c}{I}\right)-\left(\frac{v_s}{b_w d}+\frac{M_s c}{\ldots}\right) \quad (12)$$

D. *The safety level of bending[illegible]orsion-shear*

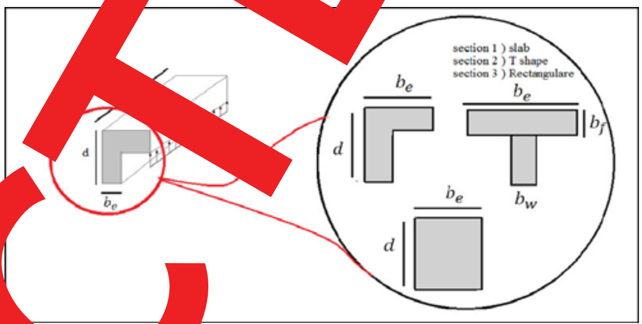
To estimate the safety [illegible] of Iranian regulat[illegible]s for the three modes of shear, [illegible]ing and torsion, the following limiting function are co[illegible]red.

$$G=\left(\frac{M_r c}{I}+\frac{2T_u(b_w+d)}{(b_w d)^2}+\frac{[illegible]}{b_w d}\right)-\left([illegible]+\frac{2T_s(b[illegible])}{[illegible]}+\frac{v_r}{b_w d}\right) \quad (13)$$

In the limitin[illegible] above, t[illegible]es of shear, bending and torsion [illegible] observed simultaneously and by considering [illegible] limit [illegible] above the safety level was estimated. T[illegible]estiga[illegible]ce of dead load on the safety level, th[illegible] value of dead load was changed.

IV. RESULTS

To investigate the safety ind[illegible] concrete beams, a section with given geometrical spec[illegible] considered as shown in Figure 1. The extensiv[illegible]d of 25k[illegible]as applied on the beam. The live load is [illegible]$_D$ and the bea[illegible]ections were L-shape, T-shape and re[illegible]lar. Choosing [illegible]e beam was in such a way that the section[illegible]f the T-sh[illegible] beam was two times bigger than th[illegible]ction ar[illegible] L[illegible]pe beam and for rectangular sectio[illegible]s as d·b$_w$. For [illegible]e, the total section and designing t[illegible] have been presented. Designing of the beam, at first [illegible]s bee[illegible]one in accordance with Iranian concrete regul[illegible]



F[illegible] of materials and dimensions considered for the studied sections

TABLE II. THE NOMINAL USED VALUES

b_w (mm)	q_D (kN/m)	f'_c (MPa)	B_e (mm)	f_y (MPa)
400	25	21	800	420
b_f (mm)	d (mm)	L (mm)	M_L=ratio*M_D=(1-t)/t	
200	400	2000	0.4-1	

[illegible]. *The safety level of regulations for states of torsion-shear*

The safety index has been calculated considering the limiting function and statistical values given in Table I. The calculation method is as follows. Nominal values such as the dimensions of the beam, the amount of shear-torsional steel, the amounts of exerted loads on the section, the concrete compressive stress and the tension of steel fluidity and etc., were considered as random variables according to Table I. Also, using the statistical values obtained such as the mean, standard deviation and statistical distribution, we have calculated the exact amount of shear force acting on the beam and the moment of torsion. The method of estimating the values of the moment of torsion and the tolerable shear force of the section was the extensive production of random numbers per each cycle written in MATLAB [16]. The Monte Carlo Method was used in procedures, which at the beginning of the cycle the values of each variable for each cycle of production, the amount of the moment and resistance (R) were calculated and at the end of each cycle the amount of load exerted on the section (S), the total load acted on the section and the moment of shear will be calculated. The safety indices in the section for various load ratios are estimated using (5).

In Figure 2, the impact numbers of Monte Carlo periodic cycles on the numerical value of the safety index are shown. This figure shows the safety index of Iranian concrete regulations for torsion and shear per different speeds. The considered section to investigate the number of Monte Carlo cycles is rectangular.

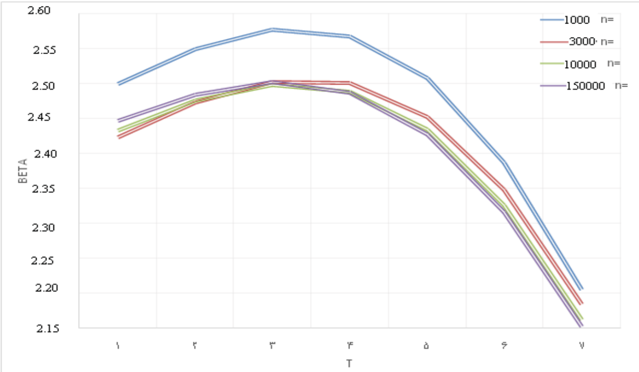


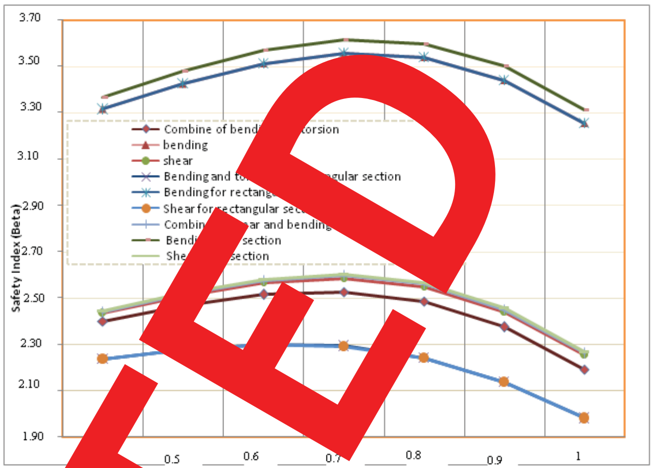
Fig. 2. Safety level

By considering Figure 2, it is clear that for all load values the recommended safety level of Iranian concrete regulations is higher than the suggested number of 2 for shear and torsion (20). Safety index reaches its maximum in number of 0.6. Also, speeding up the cycle to the number of 15000 estimates the safety level with a good approximation and for higher speeds the safety index showed little changes. As is seen in the [illegible] the calculations for the number of rounds to 10 times, i.e., [illegible] to 150,000 rounds have been done, but the safety index has [illegible] changed much. So, in follow-up research the number of simulated rounds has been limited to 15,000. As can be seen from the figure, reducing the live load [illegible]ng the numerical value of t) has led to a decline [illegible] the sa[illegible] index that is likely because of the loss of influ[illegible] of the [illegible] factor (factor of 1.5).

B. The safety level of bending-torsi[illegible]

Using the formulas presented [illegible]ier, the safety in[illegible]s calculated for loading combinatio[illegible]nding-torsion. In order to present and compare the resu[illegible] [illegible]nding levels have been shown with separated li[illegible] and the [illegible]al levels with dotted lines and the combinatio[illegible] of the consi[illegible]tates with continuous lines; the rectan[illegible]r sections are show[illegible] with blue color, L-shape section wit[illegible]d color, and T-shape section with green color. In the graph[illegible]wn below the safety index for each section has been prese[illegible]

According to Figure [illegible]r that th[illegible]gulation level of Iranian concrete for torsion [illegible] 2[illegible] to 2.70, and the average obtained i[illegible]. Also, th[illegible]on level of Iranian concrete for b[illegible] etween 3 a[illegible] 4 and the average obtained is 3[illegible]he reg[illegible]ion level of Iranian concrete is for bending and [illegible]sion is [illegible] values of bending and torsion, and [illegible]btained is 2.90 for bending-torsion. The maximum [illegible] index for combination of shear-bending occurs at t=0.[illegible]



Fi[illegible] [illegible]gulation level of Iranian concrete for bending-torsion

C. Safety level of be[illegible] shear state

[illegible]ure 4 shows the regulation safety level of Iranian concrete [illegible]or shear-bending. Figure 4 also shows the regulation level for [illegible]imit state of shear-bending. The regulation level in the [illegible]ombination of [illegible] two limit states will skew towards shear. [illegible] seen in the f[illegible]e, the regulation level at shear and bending [illegible] are ne[illegible] each other. Shear and bending levels and the com[illegible] the two states have been shown with dotted points, dotted lines and line respectively. To present and [illegible]pare the results better the results of shear levels have been s[illegible] dotted points, the combination of the considered s[illegible]es has been shown with lines, and the rectangular sections [illegible]ve been shown with blue color, the slab section with red [illegible]olor, and T-shape section with green color.

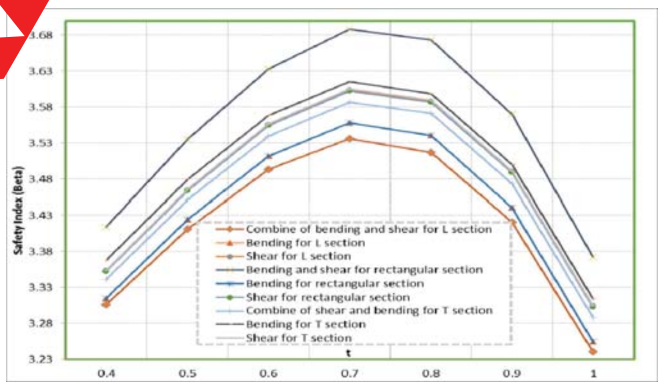


Fig. 4. Regulation of the fathers to the Sun-Bending

D. The safety level of bending-torsion-shear

Combination of the shear, bending and torsional states has been done using existing formulas. Figure 5 shows the maximum safety index for the three states above related to T-shaped section that is 3.05

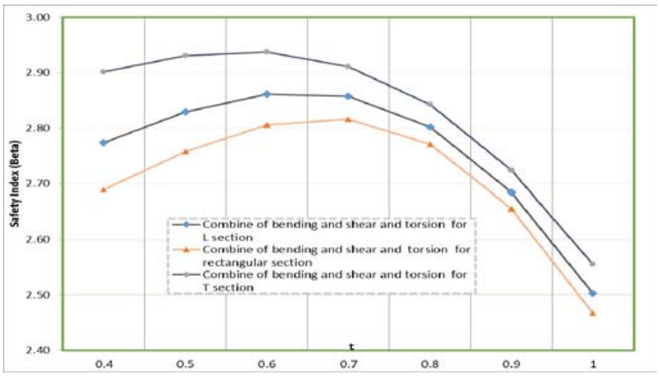


Fig. 5. Regulation level of Iranian concrete for shear, bending and torsion

E. Estimation of the regulation safety factors for limit states. Safety factors calculated with the safety index (shear-torsion-bending)

In the following section, the factors of regulations are estimated. In order to estimate the factors, only the data of the rectangular section have been used. To obtain the safety factor, at first a wide range of factors are used. Then, using the existing formulas in the Iranian concrete regulations and the applied factors, the nominal values of steel are calculated. Next, the safety index of the considered limit functions are calculated without the use of any of the factors existed in the regulations and by using Monte Carlo cycle. In Figures 5 to 8, the coefficients obtained from the Monte Carlo techn[illegible] and the intended safety index are presented. As it can be se[illegible] the figures, the estimated safety factors have a direct infl[illegible]e on the safety index and they affect the fluctuations of the sa[illegible] index. Also, it can be seen that the increase of the amount o[illegible] live load and dead load, and consequently [illegible]ducing the resistance reduction factors (steel, concret[illegible]es the safety index while the increase is linear.

Figure 8 illustrates this important iss[illegible]t at th[illegible] shear and torsion, Iranian concrete regula[illegible]close to torsion and at the states of torsio[illegible]nd be[illegible]Iranian concrete regulations are near to to[illegible]n. As can be [illegible]in figure 8, the increase of resistanc[illegible]duction factor ($\varnothing_C$, [illegible]s) reduces the safety index, becaus[illegible]fety index is directly affected by loads than resistance[illegible]d re[illegible] parameters, and the more the effect of the l[illegible] the high[illegible]safety level; Therefore, to investigate the importance of these [illegible]ctors in the safety index, the increa[illegible]f resistance factors (that leads to a decrease in safety index[illegible]d the increase of load factors (that leads to an increase in s[illegible]y inde[illegible]have been studied and the safety levels and th[illegible]affect[illegible]ty from the factors are compared and discussed.

Figures 6, 7 and 8 indicat[illegible]ith[illegible]pect to regulation formulas, the eff[illegible]tors in sa[illegible]ex at states of shear and torsion is [illegible]tive[illegible]ower than load factors and on the contrary, at [illegible] bendin[illegible] state the Iranian regulation level concrete is [illegible]ffecte[illegible] reduction factors; and at the combinatio[illegible]f torsion-bending (the index is more affected by torsion[illegible]ared with the state of shear and bending (the index is m[illegible]cted by shear), the regulation level is more affected by th[illegible]crease of resistance reduction factors and the increase in load at torsional state could not affect the safety index and the resistance factors have been more effective on safety inde[illegible]f bending-torsion. The slopes of drawn lines are i[illegible]tive o[illegible]t.

Fig. 6. Estimation of the factors used in Iranian concrete regulations for shear-bending

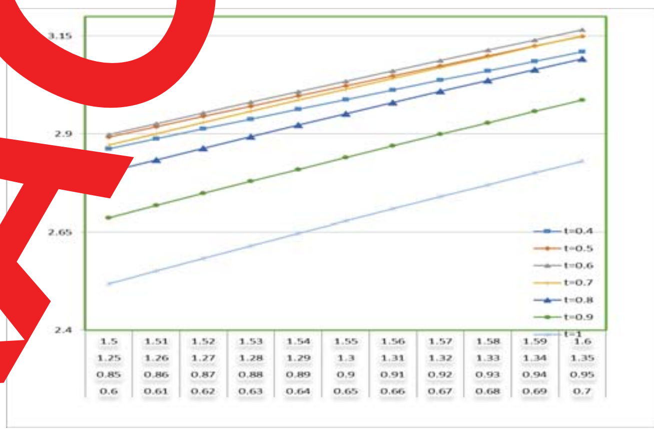


Fig. 7. Estimation of the factors used in Iranian concrete regulations for torsion-shear

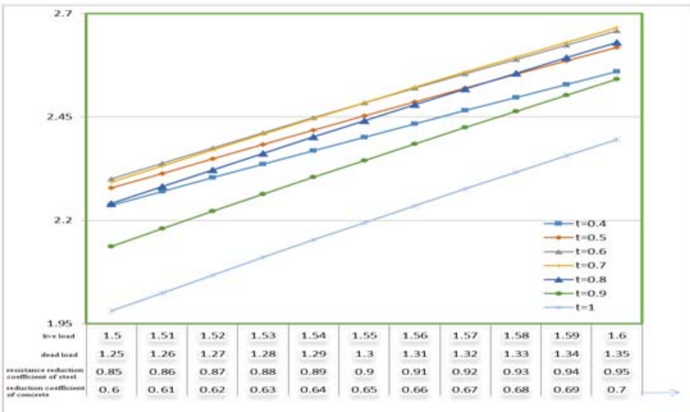


Fig. 8. Estimation of the factors used in Iranian concrete regulations for bending-torsion

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The following conclusions can be obtained:

- At bending state and its combination with torsion, the regulation level is more affected by resistance reduction factors and the increase of these factors decreases the safety index further.
- According to the dimensions and load given, the regulation level is affected by shear steel. Certainly, the change of dimensions leads to the changes in used steel and the rate of affectability from shear because the size and composition of load directly affect the safety level.
- The regulation level of Iranian concrete at general state of the combination of bending-torsion-shear at t=0.7, 0.9, &1 is affected by the increasing of load factors and at t=0.4-7 the regulation level is affected by resistance reduction factors; therefore the increase of live load to dead load directly affects the safety level in all regulation states.
- For an increase of the amount of t=0.7, 0.9, &1 in the state, the shear is effective and consequently the increase in load factors have more power for increasing the safety index, because in these states the increase of the effect of the live load factor has affected the safety level.
- The absolute values of the slope of the drawn lines are the power of the factors in changing the numerical value of the safety index.

V. Conclusion

This study investigated the safety level of Iranian co[illegible]te regulations for limited combinations of torsion-shear-ben[illegible] and obtained the regulation safety level of Iranian design[illegible] using the Monte Carlo technique. The basic results are as follows:

- The safety index obtained for bending, [illegible]ar, and [illegible]sional state is set between 2 and 3 (consider[illegible]hat in s[illegible] the safety level is higher than at the b[illegible] and in the bending state it is higher than at [illegible] torsio[illegible]).
- The combinations of limit stat[illegible] for shear, tors[illegible] bending are near to the safety [illegible]ex of shear and in [illegible] combinations reaches to its m[illegible]vel which indicates that the increase level of th[illegible]e loa[illegible] and dead load factor are at their maximu[illegible]vel.
- An increase in the secti[illegible]rea will increase the s[illegible]fety level of regulations; becau[illegible]t the amount of fixed load the increase in concrete[illegible]ults to [illegible]e reduction of resistance factors that directly [illegible]ct the [illegible]ty index.
- At all calculated loa[illegible] the reg[illegible]ion level is set higher than the recommend[illegible]ty i[illegible]x, which indicates that factors e[illegible] regulatio[illegible] result to an unsafe design. Cer[illegible]y, c[illegible]ing of the d[illegible]ensions of the beam and also [illegible]rate o[illegible]erted loads will affect the safety index. T[illegible]fore, a[illegible]on regulation principles results in c[illegible] safety in different conditions; so the accurate desig[illegible]be done with careful study and clarification of the u[illegible] goals according to the lifetime of the considered structur[illegible]

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