Assessment of the current acceptance criteria for concrete compressive strength

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In this paper, an assessment of the current two acceptance criterion of the Egyptian code for concrete compressive strength as tested by standard cubes was conducted. Actual determination of the statistical parameters for compressive strength data for fourteen different projects has been evaluated. It revealed a normal distribution with a bias factor ranging from 1.23 to 1.58 and a coefficient of variation spanning the range 5.5 % to 22.6 %. It has been shown that the second accepting criterion of the Egyptian code is very difficult to fulfill. A reliability analysis using Monte Carlo simulation technique with full and truncated distributions of variables has been developed. The main focus of this analysis is to evaluate the probability of failure of both columns and beams due to the variability of concrete compressive strength. Three levels of concrete compressive strength have been considered namely; 250, 350, and 450 kg/cm^2. Results have shown that the first acceptance criterion of the Egyptian code suffices to assure a target reliability index of 3.0 provided that the data coefficient of variation does not exceed 17.5 % for all strength levels. Furthermore, an additional condition has been proposed for extreme cases where the coefficient of variation exceeds the 17.5% for all strength levels. This condition has been developed through truncated distribution which imposes a minimum strength for achieving a target reliability index. The minimum strength, which is related to the characteristic strength, has shown the dependency on the strength level, the value of both the data bias factor and the data coefficient of variation.

فى هذا البحث تم تقييم شرطى القبول لمقاومه الخرسانة للضغط طبقا للكود المصرى لتصميم و تنفيذ المنشآت الخرسانية وذلك بناءا على ثلاث أسس وهى بيانات حقيقية لنتائج تكسير مكعبات خرسانية قياسية لعدد أربعة عشر مشروعا تم تنفيذهم و التحليل الإحصائى و دراسة الإعتمادية (Reliability) لكمرات وأعمدة مصممة طبقا للكود المصرى. وقد أظهرت النتائج الإحصائية لهذه المشاريع أن التوزيع الإحصائى لهذه النتائج يتبع توزيعا إعتدالى (Normal) ومعامل الإنحياز له (Bias) يتراوح بين ١,٢٣ إلى ١,٥٨ و معامل التغير بين ٥,٥ و ٢٢,٦ %. وقد أظهرت الدراسة صعوبة أن ينطبق الشرط الثانى من شروط القبول إحصائيا و كذلك من خلال النتائج الحقلية. و قد تم إستخدام طريقة المحاكاة "مونتى كارلو" وعمل برنامج للحاسب الآلى وذلك لتوليد توزيعات عشوائية كاملة و مبتورة لدراسة وتقييم معامل الإعتمادية لعدة أعمدة وكمرات مصممة طبقا للكود المصرى. أوضحت النتائج أن الشرط الأول للقبول فى الكود المصرى يكفى وحده لتحقيق معامل إعتمادية مستهدف مقداره ٣,٠ شريطة ألا يتعدى معامل التغير قيمة ١٧,٥ % لمستويات مقاومة الخرسانة التى تم إعتبارها فى هذا البحث (٢٥٠ و ٣٥٠ و ٤٥٠ كج/سم^2). وبالنسبة للقيم الأعلى لمعاملات التغير فقد تم إقتراح شرط إضافى للقيمة الدنيا للمقاومة التى يتم تحقيقها فى الموقع منسبة إلى مقاومة الخرسانة المميزة طبقا لرتبة الخرسانة و معامل التغير وقد تم تعميم جميع هذه الشروط فى جدول واحد يساعد على تقييم تحقيق مقاومة الخرسانة لمعامل إعتمادية مستهدف.

Keywords: Acceptance criteria, Concrete, Compressive strength, Reliability, Simulation

1. Introduction

Current Egyptian code for Reinforced Concrete (RC) design [1] calls for two accepting criteria for concrete cube compressive strength. The first criterion is that only 5% of the individual strength values, as tested by standard concrete cubes, are allowed to fall below the characteristic compressive strength. The second criterion establishes that the difference between the highest and lowest strength values shall not exceed 25% of the average strength value. It is also stated that, if the second criterion is not met, the decision is left to the project consultant for considering whether the concrete strength satisfies its characteristic strength or not.

It is inevitable to produce concrete without having some of the test specimen results lower than the characteristic strength. Thus, the main purpose of the first criterion is to ensure that most of the strength test results are fulfilling the characteristic strength. The first criterion in the Egyptian code is similar to those of most codes, e.g. ACI 318 [2], but with different failing percentage. With respect to the second criterion, it is a measure of data dispersion, where the range (R_g) is used in this regard. Statistically, it has been well established that the range is not a good measure of data dispersion for large data points [3], as one data point, whether high or low, might affect the range adversely. The other measure of data dispersion, which is a better measure for large data points, is the standard deviation. The ACI 214 [4] provision adopted the standard deviation as a reflection of concrete quality. However, the standard deviation in itself without being related to the average strength value is questionable as the same standard deviation might indicate superior quality for high strength concrete, and poor quality for normal strength concrete [5]. It is worth mentioning, as will be shown later, that the first acceptance criterion of the Egyptian code includes the standard deviation measure implicitly.

The main focus of this study is to evaluate the acceptance criteria of the Egyptian code in view of available actual strength data for several projects. Cube compressive strength data for fourteen projects were collected and analyzed. The approach adopted for this evaluation is the reliability analysis, where the probability of failure, for RC section under concentric compressive loading and bending loading, is assessed.

2. Evaluation of actual strength data

Evaluation of actual test strength has been based on fourteen projects. In order to get representative data, the projects were selected such that the site quality control for these projects ranged from very good to poor according to ACI 214 classification [4]. In this study, the concrete compressive strength was defined as the strength obtained from the standard cube (150 mm) tested as per the Egyptian code. Summary of the strength data for the projects are given in table 1, where each data point is an average of three strength test results. The table gives the number of data points (n_s), the average strength (f_{cm}), the standard deviation (σ), the maximum strength value (f_{max}), the minimum strength value (f_{min}), the range (R_g=f_{max}-f_{min}), the ratio (R_g/σ), the characteristic compressive strength of the project (the design value) (f_{cu}), the ratio (f_{min}/f_{cu}), the ratio (R_g/f_{cm}), the coefficient of variation ($COV=\sigma/f_{cm}$), and the bias (mean to nominal) factor ($\alpha=f_{cm}/f_{cu}$). Furthermore, the achieved characteristic strength (f^*_{cu}) were included in the table, where $f^*_{cu} = f_{cm} - 1.64\sigma$ as per the first criterion of the Egyptian code eq. 1-a. All these values were used to evaluate the actual strength data as will be shown in the following sections.

3. Type of distribution

Data evaluation in most design codes is based on the assumption that the statistical distribution of the compressive strength data follows a normal distribution [6-8]. Fig. 1 shows the Cumulative Density Function (CDF) for the actual strength data points of the fourteen projects considered in this study plotted on normal probability paper. It is evident that the distribution is normal for all data points as the CDF's almost follow a straight line.

4. Acceptance criteria

According to the Egyptian code, one can simplify the first acceptance criterion as:

$$f_{cm} \geq f_{cu} + 1.64\sigma \,, \tag{1-a}$$

by substituting $\alpha=f_{cm}/f_{cu}$, and $COV=\sigma/f_{cm}$ and rearrange, the following inequality can be deduced:

$$\alpha \geq 1/(1-1.64COV) \,. \tag{1-b}$$

This inequality relates the bias factor (α) to the Coefficient Of Variation (COV) of the first criterion. The importance of this inequality is that it contains several factors describing the whole statistical characteristic of the strength distribution. The data dispersion is implicitly included in the COV as well as the mean value. Also, the bias α reflects how far f_{cm} is from f_{cu},

Table 1
Summary of the fourteen projects' strength data

Project	n_s	f_{cm}	σ	f_{max}	f_{min}	R_g	R_g/σ	f_{cu}	f_{min}/f_{cu}	R_g/f_{cm}%	COV %	α	f^*_{cu}
P1	575	372	60.6	553	199	354	5.84	250	0.80	95.1	16.3	1.49	273
P2	135	333	49.7	440	214	226	4.55	250	0.86	67.9	14.9	1.33	251
P3	98	315	49.4	445	215	230	4.65	250	0.86	73.0	15.7	1.26	234
P4	87	446	76.0	587	282	305	4.01	300	0.94	68.4	17.0	1.49	321
P5	150	376	56.2	516	244	272	4.84	275	0.89	72.3	14.9	1.37	284
P6	51	409	67.0	530	200	330	4.93	275	0.73	80.7	16.4	1.49	299
P7	82	475	45.0	550	356	194	4.31	300	1.19	40.8	9.47	1.58	401
P8	61	413	78.0	531	237	294	3.77	300	0.79	71.2	18.9	1.38	285
P9	95	346	50.3	451	236	215	4.27	250	0.94	62.1	14.5	1.38	264
P10	90	327	70.5	469	187	282	4.00	250	0.75	86.2	21.6	1.31	211
P11	32	307	69.6	458	200	258	3.71	250	0.80	84.0	22.7	1.23	193
P12	32	330	41.5	421	256	165	3.98	250	1.02	50.0	12.6	1.32	262
P13	558	666	36.7	760	553	207	5.64	500	1.11	31.1	5.51	1.33	606
P14	98	432	42.8	491	341	150	3.51	275	1.24	34.7	9.90	1.57	362

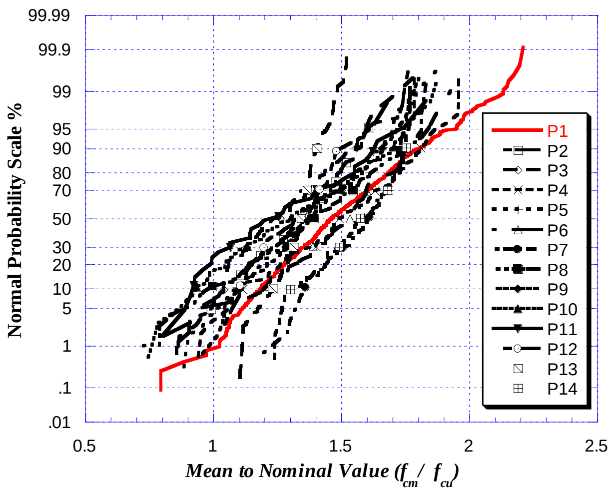

Fig. 1. CDF's of the actual strength data of the 14 projects.

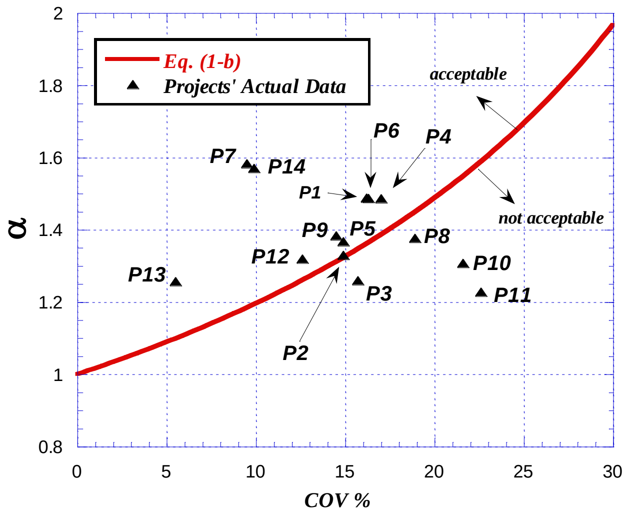

Fig. 2. First acceptance criterion and actual strength data.

indicating the probability of understrength. This issue is critical for reliability analysis. Fig. 2 shows this inequality together with the fourteen data points representing the projects in hand. It is clear that 4 of the projects did not fulfill the Egyptian code based on the first criterion.

With respect to the second accepting criterion, none of the projects has fulfilled it despite the fact that one of these projects (*P13*) is classified "*very good*" according to the ACI 214 [4]. The percentage of R_g/f_{cm}, for the fourteen projects, ranged from 31 to 95 %.

5. Values for (R_g/σ), f_{min}/f_{cu}, α and COV

The data scatter as given by the (R_g/σ) ranged from 3.77 to 5.84 with an average value of 4.423. This indicates that the assumption that all data are included in the $\pm 3\sigma$ is valid. On the other hand, the ratio f_{min}/f_{cu} for the projects ranged from 0.73 to 1.19 for the fourteen projects even after excluding the unacceptable projects based on the first criterion. This indicates that for one of the projects, the minimum strength achieved was 73 % of the characteristic strength, yet, the concrete strength of this project is acceptable. The bias factor α for the fourteen projects ranged from 1.23 to 1.58 with an average of 1.375 meaning that the average strength for all projects exceeded the design strength with a reasonable margin. The COV ranged from 5.5% to 22.6%. The range of the values is considered large, however, it is quite similar to those available in the literature6 [6,8-10].

6. Statistical background

The Cumulative Density Function (CDF) for concrete compressive strength has been shown to follow a normal distribution as revealed by many researchers [6-8] and proven for the current evaluation of the fourteen projects. Fig. 3 shows schematically the Probability Density Function (PDF) for the normal distribution of concrete compressive strength. The second accepting criterion can be expressed as:

$$(f_{max} - f_{min}) \leq 0.25 f_{cm} . \quad (2\text{-a})$$

Assuming that all the data points fall between ± $n\sigma$, where $2n\sigma$ represents the range upon which the data are scattered, thus,

$$(f_{max} - f_{min}) = 2n\sigma . \quad (2\text{-b})$$

By combining eqs. (2-a) and (2-b), and rearrange, the (COV) of the strength data, according to the second accepting criterion can be expressed as:

$$(COV = \sigma / f_{cm}) \leq (0.25 / 2n\sigma) . \quad (2\text{-c})$$

Which means that if $n=3$ (the case where 99.73% of the data points fall between ±3σ), then the COV should be ≤ 4.17% and for $n=2$ (where 95% of the data points fall within ±2σ), the COV should be ≤ 6.2% for the second acceptance criterion to be met. It should be stated that the assumption of 2n or 3n is statistically typical and is a very reasonable as demonstrated before in the actual strength data analysis. It has been shown before based on the actual statistical data that these values of the COV's are too small and very difficult to achieve. The *COV*, as in the actual data of the fourteen projects, ranges between 5.5 to

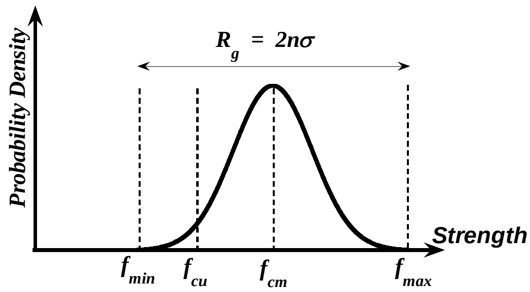

Fig. 3. PDF of concrete compressive strength.

22.6%, and even in the literature, the typical value of actual *COV* ranges from 10 to 20% [6,8-11]. All these evidences institute the difficulty of achieving the second accepting criterion of the Egyptian code.

7. Critical evaluation

As mentioned before, ten of the projects considered in this study have fulfilled the first acceptance criterion of the Egyptian code. None of the projects has satisfied the second one, which implicitly means that the second criterion may have been waived by the consultant engineer as per the code for all the projects. A question arises regarding the safety of the structures made of a certain concrete accepted based on the first acceptance criterion only. In other words, the first accepting criterion grantees that only 5% of the results fail to achieve the characteristic strength; however, it does not ensure that the structure elements are safe as the criterion does not check the understrength values.

The safety of the structural elements under any case of loading can be assessed based on the reliability analysis. The main concept and details of this type of analysis are explained elsewhere [9,12]. Generally, the analysis is based on a chosen limit state function (g) where;

$$g=R-Q, \quad (3)$$

where R is the member strength and Q is the load effect. The safety of the structural element against failure is defined by a single factor β (the reliability index) which can be depicted from fig. 4 and can be computed as [13],

$$\beta = \bar{g} / \sigma_g , \quad (4)$$

where $\bar{g}$ is the mean value of g, and σ_g is its standard deviation. The probability of failure P_f is related to β through [9,12]:

$$P_f = 1 - \Phi(\beta) . \quad (5)$$

Where Φ (β) is the standard normal *CDF*, thus, the relation between β and P_f is exponential, and some of the β values and its corresponding P_f values are given in table 2.

8. Limit state functions

The limit state functions used in this study were based on the Egyptian code[1] using the assumption of maximum usable strain of 0.003 at the extreme concrete fibers in bending. Also, the equivalent stress rectangular block with a stress ordinate of 0.67 f_{cu}/γ_c was used together with an elastic perfectly plastic stress-strain relation for reinforcing steel. The limit state function in bending can be simplified as:

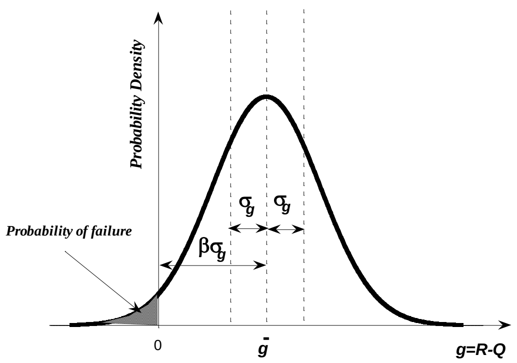

Fig. 4. The concept of reliability index [13].

Table 2
Values of β and the corresponding P_f

β	P_f	β	P_f
1.28	0.10000	3.05	0.00114
2.33	0.01000	3.09	0.00100
2.80	0.00256	3.10	0.00096
2.85	0.00219	3.15	0.00081
2.90	0.00187	3.20	0.00068
2.95	0.00159	3.71	0.00010
3.00	0.00135	4.26	0.00001

$$g = [A_s f_y d/\gamma_s][1 - A_s f_y / [2(\gamma_s / \gamma_c)(0.67 f_{cu} bd)]] - D - L, \quad (6)$$

and for concentric compressive load as:

$$g = 0.35 f_{cu} bh + 0.67 A_{sc} f_y - D - L . \quad (7)$$

Where, A_s is the steel area, f_y is the yield stress, b is the section width, d is the effective depth of the beam, h is the total section depth, A_{sc} is the total steel area in the column cross section, f_{cu} is the concrete compressive strength, D is the dead load effect, and L is the live load effect. γ_s and γ_c are considered 1.15 and 1.5 as per the Egyptian code [1].

9. Statistical parameters of the variables

In order to conduct a reliability analysis, the statistical parameters of all variables considered in the limit state function should be available. These parameters are; the mean, bias, standard deviation, and the type of distribution. For reinforcing steel, these parameters have been evaluated before by the author based on 561 test results representing most of steel types available in the Egyptian market [14]. Summary of this analysis is given in table 3 for both yield stress and bar cross-sectional area. The study covered a range of nominal bar diameters between 8 and 32 mm, where no correlation has been found between the bar diameter and yield stress. The nominal steel yield stress *n* this analysis was considered 4000 kg/cm^2.

For the statistical parameters of section dimension, they are always considered to be in the form of $x \pm \Delta$, where x is the nominal value and Δ is a dimensional factor [16,18]. The allowance permitted by the Egyptian code [1] is considered (e.g., Δ=±10mm for the effective depth of the beam and ± 5 mm for beam width). The standard deviation of each dimension was evaluated based on the assumption that the allowance Δ= three times the standard deviation. The bias factor is considered as 1.0 and normal distribution is used to simulate the all variables of dimensions as recommended by most researchers [9,18].

With respect to both dead and live load, summary of the data available in the literature regarding their statistical characteristics were summarized elsewhere [14]. Parameters considered in this study are given in table 3.

11. Reliability analysis

Reliability analysis is a powerful tool for considering the variability of both materials and loading to assess the probability of failure for structural elements. As the statistical distributions of the variables in this study were found to be distinctly different, the direct application of reliability model techniques is not feasible [12]. Thus, it was decided to utilize the Monte Carlo simulation technique throughout.

The main focus of the reliability analysis was to estimate if the first acceptance criterion of the Egyptian code is enough or not to ensure certain reliability index. This has been accomplished for structural elements subjected to concentric compressive load or bending load. According to eq. (1-b), the first acceptance criterion at the limit (i.e. the points on the curve in fig. 2) can be expressed in terms of both *a* and *COV* for any concrete nominal strength, and consequently, the reliability indices were evaluated at this limit.

For concentric compressive load cases, three cross sections denoted C1 to C3 were chosen and given in table 4. Also included in this table, are three rectangular cross sections B1 to B3 for bending loading. All column sections were reinforced with a typical 1% reinforcement, while all beam sections were designed as under-reinforced sections as per the Egyptian code [1]. Three different levels of concrete strength (250, 350, 450 kg/cm2) have been selected for each case of loading and section.

12. Monte Carlo simulation

Full details for the general purpose Monte Carlo simulation technique are available elsewhere [12]. In this study, two types of simulations have been considered; the full distribution, and the truncated distribution. In the former, the variables are generated over the entire range of ± ∞ without any intervention during generation. On the other hand, truncated distribution is generated by the intervention during simulation such that the minimum value of the generated variable should not be lower than a certain pre-defined value. This predefined value is set prior to the simulation and is related to the nominal value of the variable through the coefficient λ(λ<1.0). As will be shown in the subsequent sections, this technique is very useful in estimating the minimum concrete compressive strength required to achieve a certain target reliability index. A computer program has been developed to generate the variables using either type of distribution and its flow chart diagram is shown in fig. 5.

13. Effect of number of realizations

The number of realization in each simulation has been examined for both concentric compressive load and bending. Several trials with a number of realization (n_f) of 1000000, 200000, 100000, 50000, and 25000 have been tried. Also, the mean dead/live load ratio has been altered from 0.4 to 2.2 with an increment of 0.2. Fig. 6 shows the results of these trial simulations revealing

Table 3
Statistical parameters of variables

Variable	Bias (*a*) %	*COV*	Type of distribution	References
Yield stress (MPa)	1.105	9.46	Extreme type I	[14]
Bar area	0.99825	2.08	Extreme type I	[14]
Dead load	1.00	0.10	Normal	[6,15,16]
Live load	1.05	0.20	Extreme type I	[15,17]

Table 4
Details of the dimensions and reinforcement of the studied sections

Section	*b* (cm)	*h* (cm)	*d* (cm)	A_s or A_{sc} (cm²)
C1	20	60	56	12
C2	30	80	76	24
C3	60	60	56	36
B1	20	60	56	6*
B2	30	80	76	12*
B3	100	20	18	12*

* Reinforcement at tension side only

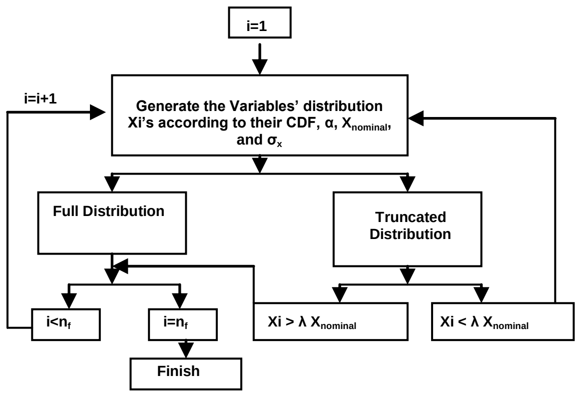

Fig. 5. Flow chart of monte carlo simulation.

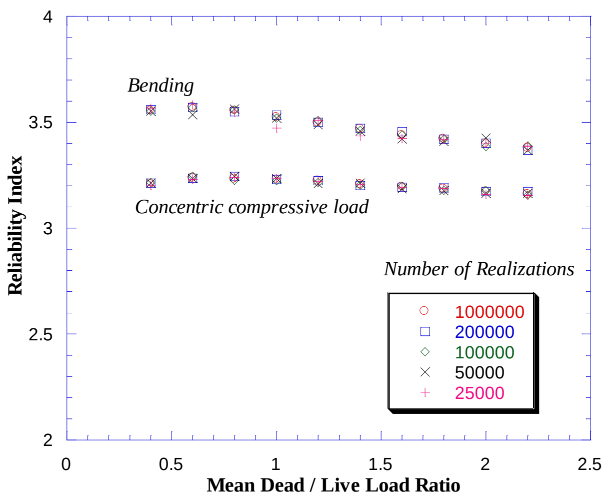

Fig. 6. Effect of number of realizations and mean dead/live load ratio on reliability index.

that very close results are obtained for most of the simulations regarding the number of realization. It was decided to use 50000 realizations throughout this study. With respect to the mean dead/live load ratio, it has a limited effect of the reliability index, simulations have been conducted for all ratios and only the ratio of (1.0) has been presented in this study. The minor effect of the mean dead/live load ratio has been well-established in the literature and the ratio of 1.0 was recommended [19].

14. Target reliability index

For this study, the target minimum reliability index was set to 3.0. This value is very typical for reinforced concrete elements [9,12]. It should be noted that the probability of failure is related to the reliability index via an exponential function, which means that it is extremely sensitive to any variation of β as given before in table 2.

15. Results and discussion

Results of reliability index for full Monte Carlo distribution are given in table 5 for concentric compressive loading and in table 6 for bending loading. The values for both *a* and *COV* were chosen such that they satisfy the first acceptance criterion of the Egyptian code at the limit (i.e. $\alpha = 1/(1-1.64COV)$). Also, the limits of both *a* and *COV* are selected based on the actual statistical strength data of the ten accepted projects.

Generally, it is obvious that β decreases as the strength level increases and higher *COV* leads to lower β despite the fact that the bias (α) increases. Also, both concentric compressive load and bending simulations have revealed very close results with respect to β.

For Monte Carlo simulations with full distribution, the first accepting criterion is capable alone to assure the target reliability index for both concentric compressive load and bending as long as the combination of *a* and *COV* does not exceed the values given in table 9 for different strength level. Generally speaking, for all strength levels considered in this study, the first acceptance criterion is sufficient for ensuring the target β as long as the *COV* does not exceed 17.5%. This is a vital outcome as this is a very typical value as revealed by actual strength data which means that the first acceptance criterion in itself is enough for ensuring the target reliability index. However, for higher values of *COV*, an additional condition is needed for the target reliability index to be met.

16. Proposal for extreme cases

Extreme cases in both concentric compressive loading and bending loadings are those having the *COV* exceeds 17.5% and the combination of a and *COV* satisfies the first acceptance criterion, yet, the β value is less than 3.0. In these cases, a new condition should be imposed in order to ensure that the target β is achieved. This condition is to impose a lower limit on the strength values as accomplished in study. This lower limit should be a function of the nominal strength value (i.e. the characteristic strength). In this case, the Monte Carlo simulation with truncated distribution as described before was utilized, the minimum value was imposed on each simulation (represented by λ), and the β value is calculated. Several trials have been conducted and tables 7,8 show the results. As noticed before in the full distribution simulations, the reliability indices were found to be very similar for both concentric compressive load and bending cases. Also, the β values were strength-level dependent.

17. Generalized Condition

In order to generalize the condition of acceptance, table 9 has been deduced from all results conducted before. This table establishes the minimum requirements for achieving the target reliability index of 3.0 for cases of different ranges of *COV* and different strength levels. The table classifies the acceptance conditions into two basic categories. The first category is that where the first acceptance criterion of the Egyptian code is enough to achieve the target index (with full distribution). In this category, the conditions are set as an upper limit of the *COV* value and its corresponding α for each strength level. For instance, for a characteristic strength of 350 kg/cm2, the first acceptance criterion of the Egyptian code guarantees the minimum reliability index of 3.0 as long as the coefficient of variation does not exceed 18.9 % and the condition itself is satisfied.

On the other hand, table 9 also includes the part of truncated distribution, where, the first acceptance criterion is satisfied, however, the *COV* value is relatively higher than the value of the full distribution acceptance. For instance, for the case of compressive characteristic strength level of 350 kg/cm2, and *COV* value of 21.6, the first acceptance criterion is satisfied, the minimum strength in the actual field data should not be less than 80% of the characteristic strength to achieve the reliability index of 3.0. It should be noted that some values in table 9 are not deduced from tables 5,6,7, and 8 and were obtained from additional simulations.

18. Conclusions

The current acceptance criteria for concrete compressive strength according to the Egyptian code 203-2001 have been assessed through actual strength field data, statistical analysis, and reliability analysis. The following conclusions can be drawn:

1. Generally, actual field data have shown a bias factor for concrete compressive strength ranging from 1.23 to 1.58 with a *COV* ranging from 5.5 to 22.6 %.
2. Normal distribution fits the compressive strength data for all the projects considered in this study.
3. It has been shown statistically that the second acceptance criterion in the Egyptian code is almost impossible to be met as it needs an exceptional quality control regime.
4. Higher strength level shows lower reliability index for both concentric compressive load and bending for the same value of both the bias and coefficient of variation.
5. For concentric compressive loading and bending, it has been found that the first acceptance criterion alone is enough to achieve the target reliability index as long as the *COV* of test results does not exceed 17.5% for all strength levels.
6. For *COV*'s higher than 17.5%, an additional condition should be imposed to ensure the target reliability index of 3.0.

A proposal, based on Monte Carlo Simulation with truncated distribution, is introduced for the cases where *COV* >17.4% where the minimum achieved cube compressive strength

7. should not be less than certain ratio of the characteristic strength. This ratio depends on the strength level and both the bias and coefficient of variation.

Acknowledgment

The strength data in this study have been collected and analyzed during the years 2001 through 2003. The author would like to thank the construction companies and contractors for providing the data. The author respects their request to stay anonymous.

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Received September 6, 2003
Accepted September 30, 2003