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Influence of Deficient Materials on the Reliability of Reinforced Concrete Members

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***Abstract*—**The strength of reinforced concrete depends on the member dimensions and material properties. The properties of concrete and steel materials are not constant but random variables. The variability of concrete strength is due to batching errors, variations in mixing, cement quality uncertainties, differences in the degree of compaction and disparity in curing. Similarly, the variability of steel strength is attributed to the manufacturing process, rolling conditions, characteristics of base material, uncertainties in chemical composition, and the microstructure-property relationships. To account for such uncertainties, codes of practice for reinforced concrete design impose resistance factors to ensure structural reliability over the useful life of the structure. In this investigation, the effects of reductions in concrete and reinforcing steel strengths from the nominal values, beyond those accounted for in the structural design codes, on the structural reliability are assessed. The considered limit states are flexure, shear and axial compression based on the ACI 318-11 structural concrete building code. Structural safety is measured in terms of a reliability index. Probabilistic resistance and load models are compiled from the available literature. The study showed that there is a wide variation in the reliability index for reinforced concrete members designed for flexure, shear or axial compression, especially when the live-to-dead load ratio is low. Furthermore, variations in concrete strength have minor effect on the reliability of beams in flexure, moderate effect on the reliability of beams in shear, and sever effect on the reliability of columns in axial compression. On the other hand, changes in steel yield strength have great effect on the reliability of beams in flexure, moderate effect on the reliability of beams in shear, and mild effect on the reliability of columns in axial compression. Based on the outcome, it can be concluded that the reliability of beams is sensitive to changes in the yield strength of the steel reinforcement, whereas the reliability of columns is sensitive to variations in the concrete strength. Since the embedded target reliability in structural design codes results in lower structural safety in beams than in columns, large reductions in material strengths compromise the structural safety of beams much more than they affect columns.

***Keywords*—**Code, flexure, limit states, random variables, reinforced concrete, reliability, reliability index, shear, structural safety.

I. INTRODUCTION

PLAIN concrete is a material that breaks easily under the application of a sudden load and degenerates rapidly under the influence of the environment and time. This makes it unusable in structures intended to support large loads for an extended period of time. Reinforcing plain concrete with embedded steel rebars can make the material strong, ductile and durable. The steel reinforcement gives added strength by taking up the tension stresses, while the concrete resists the compression stresses. The concrete also provides shielding for the steel so it doesn't rust with time, and together they form a composite material that is not expensive and easy to build.

Reinforced concrete is widely used nowadays in the construction industry. It offers many advantages over other construction method to owners, architects, engineers and contractors including formability, durability, economy, resistance to high temperatures, good insulation, reduced deflections, high damping, abundance of materials, and no need for skilled workers. The limitations of reinforced concrete include uncertainty of material properties, need for formwork and shoring, demand for large foundation, difficulty of inspection, inherent time-dependent deformations, and need for tight quality control measures.

The mechanical properties of materials vary from part to part, even when constructed following a tightly controlled process. These variations do not only occur from one batch and another, but also among the different parts of the same batch. In general, variability in mechanical properties of a construction material does not make the material unsafe, provided that the level of variability is known and remains constant throughout the production range. The most serious causes of variability in concrete strength are the result of errors in batching, variations in mixing, differences in cement quality, disparity in the degree of compaction, and discrepancies in curing. Similarly, variation in steel strength properties can be caused by the manufacturing process, rolling conditions, characteristics of the base material, uncertainties in chemical composition, and the microstructure-property relationships. Since the relative importance of these factors is difficult to assess accurately, design codes of practice for reinforced concrete structures employ appropriate factors of safety to ensure the adequate performance of structures over the useful life.

II. PROBLEM STATEMENT

The resistance factors in structural design codes consider the natural variations in materials. However, they do not account for the unpredictable variations in material strength properties due to deficient construction practice, unexpected structural deterioration, sudden damage, and human mistakes.

Experience has shown that improper detailing of reinforced concrete structure can lead in some instances to degradation of concrete over time. Frost action, air pollution and other types of aggressive environments can cause concrete structures to suffer unexpected severe damages. Materials which do not meet the design requirements can also cause serious load

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bearing problems. During the construction stage, inadequately concrete cover and bar spacing provisions may lead to severe strength and durability problems. Poor workmanship or lack of quality control during construction can result in honeycombs, plastic cracks, and bug holes, which greatly affect the load-carrying capacity of the structure.

From the above, it is necessary to quantify the effect of substandard concrete and steel strength properties on the load-carrying capacity of reinforced concrete members. Since loads and resistance are random variables, a reliability-based parametric analysis is performed on typical sections in flexure, shear and axial compression to determine the reduction in structural safety due to deficiencies in the concrete compressive strength or reinforcing steel yield strength beyond the natural variations.

III. LITERATURE REVIEW

A structure can be considered defective due defects in the quality of raw materials, diversion from the designed concrete mix, use of defective material processing and fabrication procedures, defective workmanship, and inadequate quality of detailing in the field. Uncertainties beyond the norm in concrete and reinforcing steel production hugely influence the strength and reliability of reinforced concrete structures. The available literature on variability in the concrete compressive strength and reinforcing steel yield strength and their effect on structural strength and reliability are surveyed.

Mirza et al. [1] reviewed the available literature on variations in concrete compressive strength, tensile strength, and modulus of elasticity of concrete. They also proposed representative probability distributions for the considered variables. The effects of volume, rate of loading, and in-situ casting of concrete were also addressed in the study. Anderson [2] used statistics and regression analysis to identify and control the variables that affect the strength of high-strength concrete. He also investigated the mechanics of optimizing the variables associated such concrete. A statistical analysis on steam-cured, plant-produced high-strength concrete cylinders in compression was conducted by Tabsh and Aswad [3]. The results of their study revealed that both the mean-to-nominal and the coefficient of variation are higher for normal strength concrete than for high-strength concrete. This finding was due the firm quality control measures employed with plant-produced, high-strength concrete. Chmielewski and Konopka [4] studied the variability of concrete strength produced in different concrete-mixing plants and transported to sites by mixer trucks. The strength of samples taken from various construction sites was tested, histograms were plotted, and statistical data were estimated. The type of the probability distribution of the variables was determined. Representative bias factors and coefficients of variations were suggested for use in the reliability analysis of concrete structures. El-Desoky and Nofal [5] investigated the variation of the 28-day to 7-day concrete strength ratio based on lab controlled concrete mixes with different relevant parameters. The variability of the concrete strength over time during construction was also studied based on data collected in the field. Results of the statistical analysis emphasized the variability nature of the 28-day to 7-day strength ratio. Diwan et al. [6] quantified the variability related to the production, construction, and testing of structural and paving concrete. Data from 900 highway projects constructed in the 1990s were collected. The analysis indicated that there was good control in the production and testing of structural concrete. Further, it was found that there was an increase in the non-uniformity of paving concrete acceptance criteria; hence, there a need to maintain better control of the variability of paving concrete through the application of control charts. Recently, Obla [7] examined the sources of concrete strength variations and concluded that they can be grouped into three categories: material, manufacturing and testing. In the material category, the variation can be due to deviations in the characteristics of cement and supplementary cement materials, coarse aggregate, fine aggregate, and admixtures. In manufacturing, Obla outlined variations in ingredient weights, mixing, transporting, delivery time, temperature, workability, and air content. Finally, in the testing category, the author highlighted variations in sampling, specimen preparation, curing, transporting, test procedures and equipment.

To develop statistical descriptors for the mechanical properties of reinforcing steel, Mirza and MacGregor [8] studied the results of about 4000 tensile tests. The sample included rebars having wide range of diameters (9.5-57.3mm) and two grades of steel (yield strength = 276 MPa or 414 MPa). The means and standard deviations of the mill test yield strengths were found to be 337 MPa and 36.1 MPa for Grade 276 steel, and 490 MPa and 45.6 MPa for Grade 414 steel, respectively. Beta distributions were used to represent the probability density function of these sets of data. Joshi and Ranganathan [9] analyzed statistical data on yield strength and modulus of elasticity of reinforcing steel bars from rolling mills and building sites. At 5% level of significance, it was found that the normal distribution can best represent the data on yield strength, while the lognormal distribution can fit well the data on modulus of elasticity. In a study on steel reinforcing bars used in Turkey, Akyz and Uyan [10] agreed with the requirements of Turkish Steel Rebar Specification Standard TS-708. In Saudi Arabia, Arafah [11] used an experimental program to develop probabilistic models for compressive strength of concrete and yield strength of reinforcing steel produced in the country. A total of 955 concrete samples and 434 samples of steel bars were randomly collected from construction sites. The results of the experimental testing indicated that ready mixed concrete can be modeled by normal distribution; whereas site mixed concrete is better represented by log-normal distribution. Variations in the yield strength of reinforcing steel are modeled by normal distribution, with a bias factor. Recently, Galasso et al. [12] carried out statistical analysis of reinforcing steel properties based on about 200 test data. The data included a wide range of reinforcing steel bars with diameter between 12 and 26 mm made in Italy. The tests results were analyzed to determine the appropriate cumulative distribution function for yield and ultimate strengths. Comparison with previous tests confirmed that there is an improvement in quality and ductility of materials and a reduction in strength variability for the considered steel.

IV. SAMPLING AND TESTING PROCEDURES

Construction materials engineering and testing is a critical component in the process of transforming a structural design into a constructed facility. It is required to ensure that the materials and their constituents are in compliance with the specification. However, the test results will be meaningless unless the sampling and testing procedures are strictly followed.

A.Concrete

The compressive strength of concrete is the most commonly used performance measure by structural engineers. It is measured by breaking cylindrical or cube concrete specimens in a compression-testing machine. The compressive strength is computed as the pressure on the specimen at the onset of failure. Strength test results from cast specimens may be used for quality control, acceptance of concrete, estimating the concrete strength in a structure for the purpose of form removal, or for evaluating the adequacy of curing and protection afforded to the structure. Hardened concrete 150 mm by 300 mm cylinders are tested for strength in accordance with ASTM C 39 [13]. A test result is the average of at least two standard-cured strength specimens made from the same concrete sample and tested at the age of 28 days. The concrete mixture is expected to give an average strength higher than the specified strength, in order to reduce the risk of not complying with the strength specification. To comply with the strength requirements of a job specification, the averages of three consecutive tests should equal or exceed the specified concrete compressive strength, f'_c. Furthermore, no single strength test should fall below f'_c by more than 3.45 MPa, or by more than 10 percent of f'_c when f'_c is more than 35 MPa.

B. Steel

The tensile strength of reinforcing steel bars is usually measured following the ASTM standard related to the type of steel used on the project. The characteristics of the material, as represented by the test specimens, must conform to the nominal tensile properties included in the specifications. Test specimens shall have a length enough to provide for a 200-mm gage length, a distance of at least two bar diameters between each gage mark and the grips, plus sufficient additional length to fill the grips completely leaving some excess length protruding beyond each grip [14]. The unit stress determinations on full-size specimens is be based on the nominal bar area. For billet steel, one tension test is made of the largest size rolled from each heat, defined as a single melting operation in a furnace [15]. For rail and axle steel, one tension test is taken from each lot of 9 tons [16]. For low alloy steel, one tension test shall be made of each bar size rolled from a heat [17]. If any tensile property of any tension test specimen is less than that specified, and any part of the fracture is outside the middle third of the gage length, a retest is allowed. Also, if the results of an original tension specimen fail to meet the specified minimum requirements and are within 14 MPa of the required tensile strength, within 7 MPa of the required yield point, or within 2 percent of the required elongation, a retest shall be permitted on two random specimens for each original tension specimen failure from the lot. In that case, both retest specimens must meet the requirements of the specification.

V.OBJECTIVES AND SCOPE

While structural design codes and standards do not replace well founded engineering, good judgment and experience, such documents are very helpful guidelines in ensuring minimum requirements. Design codes of practice for reinforced concrete structures consider the materials' natural variability through the use of resistance factors. Other variations due to human errors in fabrication, concrete casting, and construction are not included in the resistance factors. Hence, to study the influence of deficiencies in material strength beyond those considered by the code, one needs to carry out reliability-based parametric analysis.

In this study, the effects of out-of-norm reductions in concrete and reinforcing steel strengths from the specified nominal values on the nominal strength and structural reliability are investigated. The considered limit states are flexure, shear and axial compression following the latest ACI 318 code [18]. Structural safety is measured in terms of a reliability index using the Rackwitz-Fiessler method [19]. And statistics of ultimate strength and load effects are compiled from the available literature [20], [21].

VI. ACI 318 DESIGN PROVISIONS

In the Strength Design method of the ACI 318 code [18], the ultimate capacity of a member shall be greater than the factored load effect:

$$\phi R_n \geq \sum_{i=1}^{n} \gamma_i \, Q_i \tag{1}$$

where R_n = nominal (expected) strength, γ_i = load factor for load component i, Q_i = load effect due to load component i, ϕ = resistance factor, and n = number of load components.

The magnitude of the load factor γ_i reflects the predictability of the load under consideration. The factored load combinations in ACI 318 that involve dead load, D, and live load, L, only are:

$$U = Maximum \begin{cases} 1.4D \\ 1.2D + 1.6L \end{cases} \tag{2}$$

The resistance factor, ϕ, depends on the uncertainty in material strength properties, variability of dimensions of members, accuracy of design equations, mode of failure of member, and consequences of failure. The resistance factors for the flexural (tension-controlled condition), shear and axial compression (tied columns) limit states are 0.90, 0.75 and 0.65, respectively.

The nominal flexural capacity based on ACI 318 is:

$$M_n = A_s f_y \left(d - 0.59 \frac{A_s f_y}{f_c' b}\right) \tag{3}$$

where A_s = area of tensile reinforcement (mm^2), f_y = yield strength of tensile reinforcement (MPa), d = effective depth of reinforcement from extreme compressive fibers (mm), f'_c = compressive strength of concrete (MPa), and b = width of the beam (mm).

The nominal shear strength, based on the ACI 318 code, is obtained by adding the contributions of concrete and stirrups:

$$V_n = 0.17\,\lambda \sqrt{f_c'} b_w d + \frac{A_v f_{yt} d}{s} \tag{4}$$

where λ = factor that accounts for the density of concrete, b_w = narrowest width of the cross-section (mm), A_v = cross-section area of vertical stirrups per spacing (mm^2), f_{yt} = yield strength of vertical stirrups (MPa), and s = spacing of stirrups along the beam length (mm).

The nominal axial compressive strength of a short column is obtained by adding the contributions of the concrete and longitudinal steel, and with consideration of a 20% reduction in strength due to minimum eccentricity of applied load:

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

where A_g = gross cross-sectional area of the column (mm^2) and A_{st} = area of longitudinal steel (mm^2).

VII. STRUCTURAL RELIABILITY CONCEPTS

Reliability methods have been successfully used in the past for evaluating the safety of reinforced concrete structures [22]. These concepts are based on the development of a limit state, defined as the boundary beyond which the member can no longer functions. The margin of safety, G, is the difference between the resistance of the structural member, R, and the effect of the applied loads, Q. It is represented by:

$$G = R - Q \tag{6}$$

Since loads and resistance are random variables, any combination of them becomes also a random variable. Safety can be conveniently measured in terms of a reliability index, β, defined as the ratio of the mean to the standard deviation of the safety margin G:

$$\beta = \frac{\mu_G}{\sigma_G} \tag{7}$$

in which μ_G is the mean of G and σ_G is the standard deviation of G. In this study, the Rackwitz-Fiessler method [19] is used to compute the reliability index. This method is based on estimating the actual distribution by a normal function at the design point on the failure surface. The total load effect is determined using Turkstra's rule [23], which assumes that the extreme value of a combination of several loads is reached when one load takes on its extreme value while the remaining other loads are at their average values (referred to as arbitrary-point-in-time).

For the case of a normally distributed safety margin, the probability of failure, Pf, can be obtained from:

$$P_f = \Phi(-\beta) \tag{8}$$

in which Φ (.) is the standard normal probability distribution function.

Statistics for the load and resistance variables for reinforced concrete building members are taken from the published research and are shown in Table I [20], [21]. Note that the mean-to-nominal ratios for the resistance variables in Table I are based on the nominal values provided by the ACI 318 structural concrete code [18].

TABLE I
STATISTICS OF BUILDING LOAD AND RESISTANCE VARIABLES [20], [21]

Load and Resistance Variable	Mean-to-Nominal Ratio	Coefficient of Variation	Probability Distribution
Dead Load	1.05	0.100	Normal
Arbitrary-point-in-time Live Load	0.24	0.650	Gamma
Maximum 50-year Live Load	1.00	0.180	Extreme I
Flexure in RC Beam	1.19	0.089	Lognormal
Shear in RC Beam	1.23	0.109	Lognormal
Axial Compression in Tied Column	1.26	0.107	Lognormal

VIII. RESULTS

A. Reliability

Before determining the effect on structural safety of reductions in concrete and reinforcing steel strengths from nominal values, beyond those accounted for in the structural design code, a reliability study is carried out on typical cross-sections to obtain the target reliability of the ACI 318 code. The study addresses the flexural, shear and axial compression limit states, with consideration of a wide range of live-to-dead load ratios (L/D).

Results of the reliability study are shown in Fig. 1. For any given value of L/D, the reliability index β for shear is higher than that for flexure and the reliability index for axial compression is higher than that for shear. This result is expected since structural design codes favor higher factors of safety at ultimate for more brittle limit states, like shear and axial compression. Also, structural codes require columns to be more conservatively designed than beams because their failure is more critical to a building than a failure within a beam which is usually localized. The results show non-uniformity in the reliability index for the considered range of live-to-dead load ratios for all the limit states. This is especially true for the range of L/D=0-1.0. The main reason for the inconsistency in the reliability is due to the governing load combination in the design code (2), which depends on the L/D ratio. For a small L/D ratio structural design is governed by the first load combination of (2) (i.e. 1.4D), and for a large L/D ratio it is governed by the second load combination (i.e. 1.2D + 1.6 L). Thus, β sharply decreases as the L/D increases from 0 to 0.125. It then increases within the range L/D=0.125-

0.5; thereafter, β decreases but remains within a narrow range. For the common ratio of L/D=1, the reliability index for flexure, shear and axial compression is about 4, 4.5 and 5.5, respectively. These values are within target reliability indices suggested by developers of the new generation of LRFD codes [21].

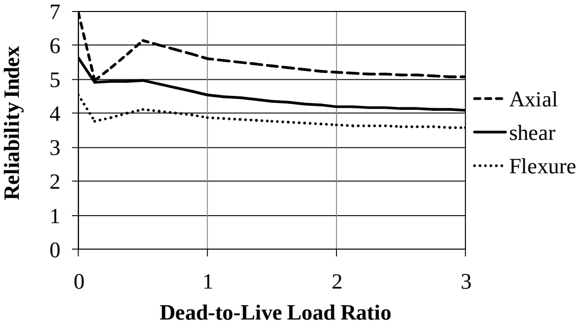
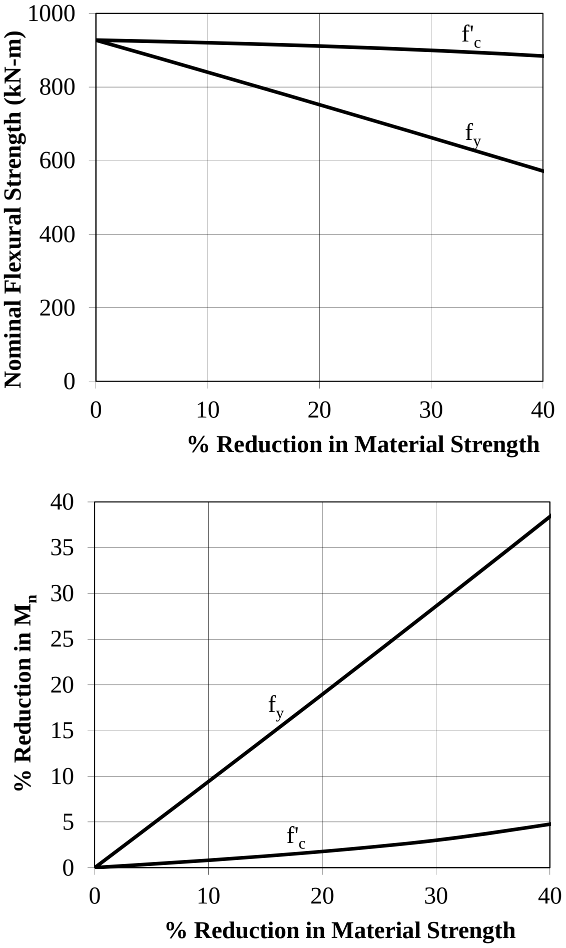


Fig. 1 Variation in reliability index with dead-to-live load ratio

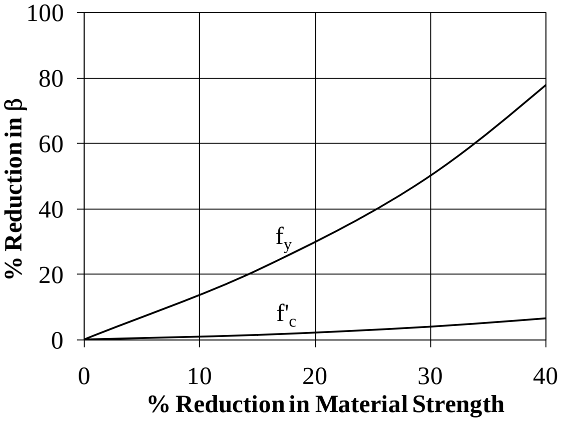
B. Parametric Study

To investigate the effect of a reduction in material properties on flexural strength, a 400mm by 800mm beam cross-section reinforced with four No. 32 steel rebars is considered. The nominal concrete cylinder strength is f'_c = 42 MPa and the nominal steel yield strength is f_y = 420 MPa. The nominal flexural capacity based on the ACI 318 code is 835 kN-m and the reliability index is 3.89. The deterministic and probabilistic analyses for flexure are shown in Fig. 2. They indicate that lower-than-expected yield strength of reinforcing steel (f_y) greatly affect the nominal capacity and reliability index. However, the effect of a decrease in yield strength on the reliability index is much more severe than on the nominal strength. On the other hand, changes in the concrete strength (f'_c) have a minor effect on both the nominal capacity and reliability index.

The same cross-section previously analyzed in flexure is now considered to study shear. The shear reinforcement consisted of No. 12 stirrups spaced at 200mm. The nominal yield strength of the stirrups is f_{yt} = 420MPa. The nominal shear capacity of the cross-section based on the ACI 318 code is 670 kN and the reliability index is 4.76. The deterministic and probabilistic analyses are shown in Fig. 3. They both show that the yield strength of the stirrups is moderately critical to the shear strength and the concrete strength has a minor effect on both the shear strength and reliability index.

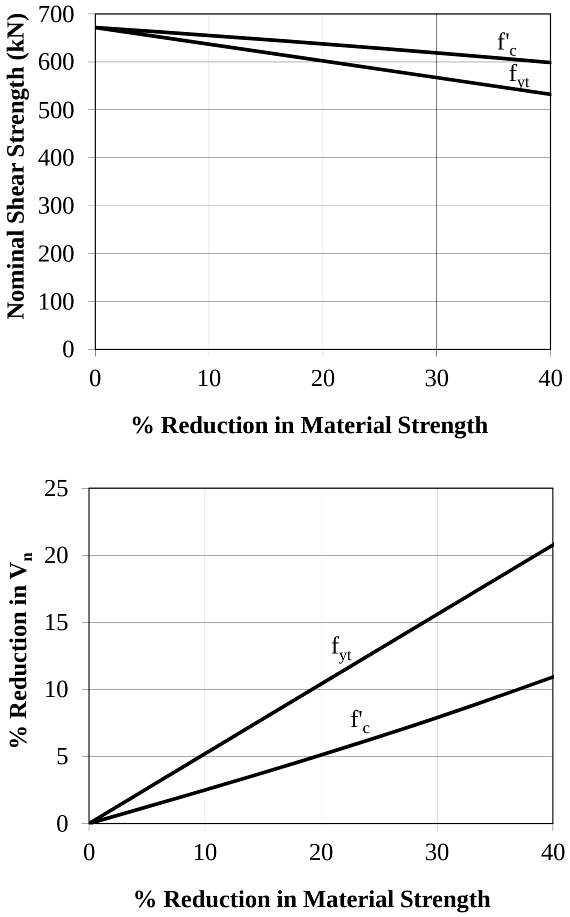


(a) Deterministic Analysis

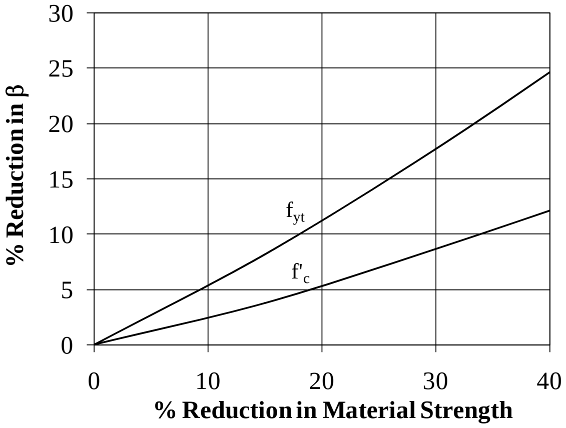


(b) Nondeterministic analysis

Fig. 2Effect of material deficiency on flexural strength



(a) Deterministic Analysis



(b) Nondeterministic analysis

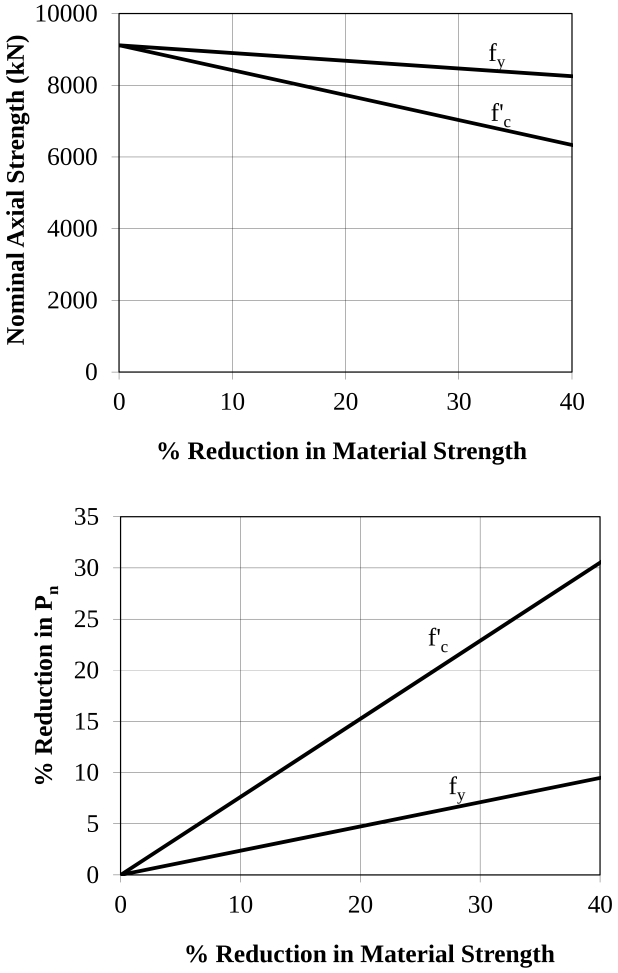
Fig. 3Effect of material deficiency on shear strength

To examine the effect of a reduction in material properties on the axial compressive capacity, a 500mm by 500mm cross-section of a tied column is considered. The cross-section is reinforced longitudinally with eight No. 32 steel bars in a symmetrical pattern. The nominal concrete cylinder compressive strength and nominal steel yield strength are 42 MPa and 420 MPa, respectively. The nominal axial compressive capacity based on the ACI 318 code is 9120 kN and the reliability index is 5.61.The deterministic and reliability analyses of the cross-section, shown in Fig. 4, indicate that lower-than-expected concrete compressive strength significantly affect the nominal capacity and reliability index. On the other hand, changes in the longitudinal steel yield strength have a minor effect on the compressive strength and reliability index.

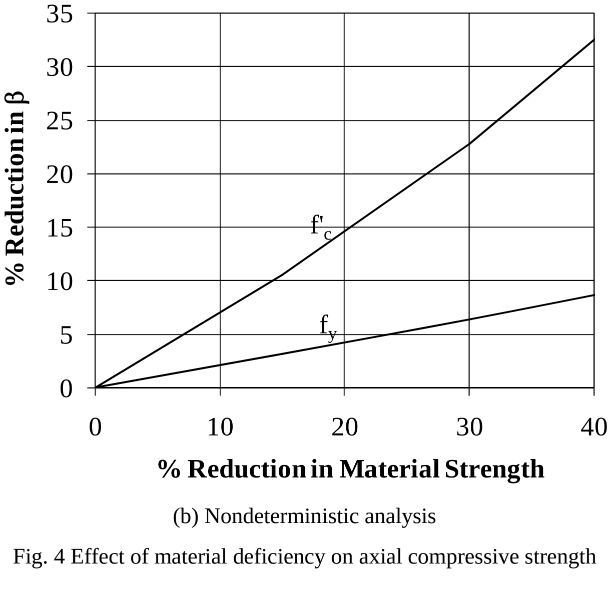
Note that the results discussed above are valid for common cross-sections with material properties and steel percentages similar to those considered in the parametric study. Cross-sections having different dimensions, materials properties, and amount of longitudinal/transverse steel reinforcement may give somewhat different results.

IX. Conclusion

The results of this study showed that there is a wide variation in the reliability index for reinforced concrete members designed for flexure, shear or axial compression following the ACI 318 code. Most of the variation in the reliability index occurs when the live-to-dead load ratio is less than 1.0.Among the considered limit states, designs based on axial compression yielded the highest reliability, followed by designs based on shear, and followed by designs based on flexure. For common material properties and reinforcement ratios, the study showed that variations in concrete strength have minor effect on the reliability of beams in flexure, moderate effect on the reliability of beams in shear and sever effect on the reliability of columns in axial compression. On the other hand, changes in reinforcing steel yield strength have significant effect on the reliability of beams in flexure, moderate effect on the reliability of beams in shear and mild effect on the reliability of columns in axial compression. Based on the above, it can be concluded that the reliability of beams is sensitive to changes in the yield strength of the steel reinforcement, whereas the reliability of columns is sensitive to variations in the concrete strength. Also, since the target reliability of beams is lower than that of columns, large reductions in material strengths reduce the structural safety of beams much more than they affect columns.



(a) Deterministic Analysis



(b) Nondeterministic analysis

Fig. 4 Effect of material deficiency on axial compressive strength

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