Reliability Basis for Some Mexican Codes

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Synopsis: A strategy is suggested for the evolution of building codes towards their ideal format; reliability optimization. Due to practical constraints the forthcoming generations of codes will probably be formulated in terms of more restricted concepts such as central safety factors or prescribed reliabilities. Explicit applications of optimization criteria are feasible at present as alternate procedures, at least for some special problems. Derivation of simplified methods for evaluation of the reliability of structural assemblages is suggested with the double aim of implementing a central-safety factor code and of setting the stage for the more advanced generations of codes to come.

Keywords: beams (supports); building codes; columns (supports); continuous beams; earthquake resistant structures; economics; failure; frames; loads (forces); optimization; probability theory; reinforced concrete; reliability; safety factor; statistical analysis; strength; structural analysis; structural design.

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Evolution of building codes and of similar documents in Mexico -- and, it would seem, in other countries as well -- is haphazard and inefficient for lack of a well defined goal: we do not know how the ideal code should look. It is time we attempted formulating the ideal. If we succeed we shall have a rational basis for proposing and scheduling the research, education and discussion needed to propose a sequence of changes in our building codes.

There are several reasons why existing codes do not constitute the ideal. The most obvious is that the safety factors, allowable stresses, seismic coefficients and other basic numbers contained in these codes have been established intuitively. There might be room for believing that, despite their dubious origin, these numbers happen to be almost what they should, they happen to lead to near optimum designs because of the power of engineering judgment. Any doubts that this could be the case are quickly dispelled as soon as we look at the coefficients' insensitivity to variables that are certainly important. Thus, our codes call for the same load factor in cantilever slabs and beams as in continuous beams while experience suggests that the former should be designed for higher load factors and an elementary reliability analysis confirms this contention, particularly when we take into account the usual discrepancies in effective depth for top steel between structural drawings and reality. Ground-story columns are designed to have the same probability of failure as penthouse columns. Other defficiencies stem from inadequate knowledge of the probability distributions of loads and actions on structures in general, of structural responses, of criteria of failure and of the consequences of failure. The situation stands in sharp contrast with recent advances in structural analysis.

A comparison of current Mexican codes and design manuals (1,2)with those of other countries shows that the former come slightly closer to the ideal documents in certain aspects despite their being more backward in others. Relatively advanced provisions include those concerning the variability of unit weights and of the discrepancies between nominal and actual dimensions of structural and nonstructural elements; design live loads as functions of tributary area; the use of "accidental" eccentricities, to be added to the computed values, for longitudinal forces in the design of columns, for wind forces and for story shears due to earthquake effects on buildings; dynamic magnification factors to be applied to statically computed seismic-shear eccentricities; reductions in some nominal cross-sectional dimensions for design of reinforced concrete members, and explicit recognition of the variability of concrete strength, as a function of the type of mix control, for establishing stress reduction factors. Backward provisions are not worth mentioning.

Despite lack of definition of the ideal code the foregoing assets of Mexican codes were probably the outcome of a vague and fragmentary image of what that document should be. A defense of those features in existing codes would be based mostly on arguments that have served to justify the use of split factors in American and European codes, plus some reasoning that has already found its way into the literature(3,4)and hence would serve little purpose here. Rather, the present paper will aim at describing and discussing what the writers visualize as the ideal code, at suggesting one way in which present codes could evolve into the ideal and at illustrating various provisions that the intermediary building codes would contain.

TOWARD THE IDEAL BUILDING CODE

What should be the purpose of building codes? -- The usual answer is "To protect public safety; soundness of investment in buildings is entirely the owner's concern." Out of oversimplification this view is quite erroneous; it does not even reflect the contents of present building codes; witness the inclusion of clauses that refer to serviceability. Clearly the main purpose of building codes should be to guard the interests of society, which are much wider than a fixed level of safety. Soundness of investments does concern society and hence should be reflected in building codes.

Even if we assumed that codes should do no more than protect public safety, the allowable level of safety would remain a moot question. Within reasonable bounds we cannot design an absolutely safe structure, one with zero probability of failure. Now, under stochastically stationary conditions, if the probability of failure is finite over any finite period of time, it is one over an infinitely long time span. It follows that every structure must fail unless it is demolished. Under the circumstances allowable levels of safety are meaningful only in the context of optimization.

On the other hand it may seem objectionable that a code should prohibit the construction of excessively safe or luxurious buildings. It might be argued that the investor should be free to spend his capital as he wishes so long as safety is not excessively endangered. If the argument were valid, codes should not contain provisions tending to limit such matters as deflections and crack widths. Capitalist countries do protect their economies by various means: they forbid the exodus of capital or the entrance of small tomatoes; they may and should, equally, try to prevent the burying of capital. It would be consistent with accepted practices, therefore, to set limits preventing the construction of overly safe or unnecessarily expensive buildings.

From the viewpoint of society a convenient objective function to maximize equals the expected present value of the benefits derived from the existence of the building minus the initial cost and the cost of damage, maintenance and failure. As a function of a design parameter, x, the benefits may vary as shown in Fig. 1. (The slow decrease with x is realistic when this parameter is, say, the diameter of reinforced concrete columns, since an increase in column size brings about a reduction in rentable area and perhaps in rentability. The benefits are practically independent of many other design parameters, such as concrete strength or steel yield stress.) As illustrated, we must subtract from the benefits the initial cost and the expected present values of the losses.

The figure also shows, by means of dashed lines, the objective function and its components, as functions of x, for a hypothetical owner. Conceivably the benefits derived from the structure's existence may be the same for the owner as for society, since in a free market the benefits derived from occupying the building are measured by the rent that the public is willing to pay therefor, and the owner will usually try to make this rent as high as possible. Conceivably, also, the initial cost may be the same for both subjects, society and owner, when that is relatively small. It is worth appreciably more to the owner when this cost is so high as to approach his total capital (including his fortune, productive power and credit worth) because of the typical nonlinear relation between money and utility. The losses due to failure may, however, be worth much less to the owner than to society if failure is not expected at an early age of the building, since the owner may contemplate an early sale and, when he does not, there remains the fact that his expected lifespan is comparatively short. Hence, the owner's objective function may attain its maximum for a smaller x than for society. Alternatively the opposite may be true, as shown by the dotted curve, if the owner has a preference for the monumental or a special aversion toward the possibility of failure.

Even when the design may not be optimal the structure is worth erecting from society's or the owner's viewpoints if and only if the corresponding objective function is positive. Hence, the building code should forbid the construction of buildings outside of this range.

It may happen, as in the figure, that there is an overlap of values of x within which it is worth erecting the building both to society and to the owner. Because of the latter's freedom the tendency will be to make the design approach his optimal solution. A compromise decision may, however, be reached owing to the engineer's and architect's divided loyalties, toward society and to their client.

The owner is a member of society and the potential satisfaction of his whims should have an influence on the shape of society's objective function. However, the building under consideration will be judged by at least thousands of the owner's contemporaries and by his and their descendants. Taking this judgment as basis for decision(5), the weight of the owner's preferences becomes negligible insofar as society's objective function is concerned, although those preferences are decisive in shaping the owner's objective function.

What we have said about a single design parameter applies equally to the rest of the structural parameters that fall within the designer's control. In general, then, rather than a plane graph, representation would demand a hyperspace; and many of the relations would not fit the smooth types of curves illustrated in the figure but would be jagged and discontinuous. The essence of the present arguments, however, is not affected thereby.

Negative values of the objective function mean that investment in other operations is more advisable than erection of the building being contemplated.

A poor architectural solution, an inefficient structural setup, the unwise use of luxurious materials or of structurally inadequate materials or the adoption of a building shape that is objectionable to the urban community may lead to a societal objective function that is nowhere positive, such as curve 1 in Fig. 2; that building should not be built. Or it may lead to a function similar to curve 2, which allows only a small tolerance about society's optimal design. The opposite situation may lead to a function such as curve 3: benefits to society are so great over such a wide range of the design parameter in question that the owner should be allowed to build the structure practically as safe or unsafe as he wishes.

Judgment about these and all other pertinent questions affecting society's objective function should ideally be settled as a consequence of public debate. Such a procedure would, however, be totally impractical. The only operative way to achieve comparable results is the setting up of an interdisciplinary committee appointed by popular election. Its sentences would be sanctioned by the possibility of reelection or removal and by public debate of its basic criteria. In the interest of efficiency the committee would pass judgment only on sufficiently important projects and on marginal instances of lesser projects; most of the latter would be approved or rejected on the basis of general rules.

In brief, then, a building code should include criteria for constructing society's objective function taking into account the most obvious variables that govern benefits, initial cost and expected losses. A committee modifies this curve as the result of its interpretation of the utility of the project to present and future generations. As a result, when there may be net positive utility, a set of recommended values of the design parameters is issued together with a set of allowable extreme values of these parameters. If there is an overlap with the range that is convenient to the owner, a compromise solution, near optimal for both owner and society, is finally produced by the engineer and the architect.

Up to this point, mention has been made only of the function of building codes in norming some of the relations between society, the owner and the designer. It is also proper that the same documents norm some relations between owner and builder, at least insofar as these relations may influence the benefits to society. To a limited extent this is done in present codes when they are made to contain clauses that refer to construction tolerances in geometry and in mechanical properties of materials. Codes as a rule are deficient in stipulating what should be done when such tolerances are not met. Rational bases are apparently lacking for the fixing of the tolerances and of the actions that should be forthcoming when the tolerances are violated. The problem can be understood by devoting attention first to these actions. The most elementary and drastic measures that are ordinarily taken consist in either condoning, strengthening, or demolishing and rebuilding. These actions are sometimes self defeating or wasteful to owner, builder and society. A first approximation to a rational approach can be based on the premise that the utility to the owner should not be affected by differences between the design and the building as built. If the contractor behaves then so as to maximize his own utility, the utility of society will be approximately maximized.

From the appearance of things it seems that neither authorities nor investors nor perhaps professionals are ready for the ideal type of code. Evolution is essential for its eventual production and acceptance. But it is eqqally essential that the goal of the evolutionary process be at least cursorily outlined, as has been done here. This permits computing a bonus that the builder should receive from the owner, or a penalty that should be applied, as a function of how well the specified strengths and geometrical properties were met. The approach has been developed for concrete strength under the assumption that the disturbances are the combination of time independent, random-magnitude loads and a generalized Poisson process, such as may correspond to the combination of gravity forces and earthquake or wind disturbances (6).

A more realistic and ambitious formulation would take into consideration changes in utility to society, as brought about by discrepancies between construction drawings and the actual structure as well as the effects of stimuli, such as bonuses and penalties to the contractor. The specification of tolerances would result from the calculation of the economic advantages in accountancy derived from the omission of bonuses and penalties when the discrepancies were sufficiently small; requirement for strengthening, or demolishing and rebuilding as the case may be, would be the natural outcome of extremely high penalties.

A strategy must now be devised to design the evolutionary process toward the ideal code. In so doing we should keep in mind the educational function of codes. This comes about through the need which everyone has to study in order to apply the code as well as through its incorporation in text books and in the didactic material of courses in the undergraduate, graduate and continuing-education curricula. But the steps from one code to the next should not be so great as to demand a discouragingly high effort. And a successful evolution requires that design aids be available when a new code is adopted. The fact that not all engineers adapt at the same rate makes it most desirable to stipulate alternative procedures in building codes in such a way that the most advanced criteria in one edition become the least advanced in the next version of the code. Experience with the introduction of ultimate strength is eloquent in this respect and suggests the most appropriate rate of innovation in each country.

Whatever format is adopted as a first step in the evolutionary process we shall not escape the need to specify nominal or characteristic values of loads and material strengths, and indeed the ideal code ought to contain changes to this effect. This is a consequence of the function of codes in regulating relations between owner, designer and builder, or of establishing bases for fixing responsibilities, which in itself may be desirable, and it is most useful as a means toward optimization for society. However, the nominal values constitute no more than point estimates of the variates, and formulating design expressions and optimization criteria in terms of those values in addition to other parameters of the distribution leads to unnecessarily complicated expressions. This is already apparent in Cornell's second-moment format (7) despite its not dealing with optimization. Hence, it is advisable to keep both types of variate characterization separate; one of these should use nominal values to establish responsibilities, bonuses and penalties, while the other should be expressed in terms of expected values and standard deviations or coefficients of variation so as to produce sufficiently simple expressions.

There is a second advantage in the use of nominal values of which one would not like to be deprived. This refers to their place in defining the most significant portion of the probability distributions of interest, as nominal values lie near the lower tail of strengths and near the upper tail of loads. The traditional statistical criteria of parameter estimation tend, in some sense, to minimize the discrepancies between the actual probability distribution and the one derived from the estimated parameters throughout a wide, central range of the variable in question. For design purposes one would like to give greater weight to the fit in the range of exceptionally low strengths and in that of exceptionally high loads. A.L.L. Baker's way of computing the standard deviation, in which he only takes into account strengths smaller than the mean (8), is an intuitive step in this direction. The same is true of code requirements and specifications worded in terms of "minimum guaranteed" or nominal strengths. The most desirable criterion for estimation of proba-