STRUCTURAL FAILURES AND THE SIDE BENEFITS OF SEISMIC CODES

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SUMMARY

Cost increases in the design, planning, and construction of structures that result from seismic safety requirements often invite strong reactions from project investors and, sometimes, even from engineers. On the other hand, moral, social and professional considerations dictate that earthquake hazard cannot be ignored without unacceptable increase in risk to the community. The present paper focuses on serendipitous benefits, those beyond a mere decrease in seismic risk, that materialize from the application of more advanced building codes. Several case histories of structural failure are discussed in the context that deleterious conditions which led to serious problems in structural integrity would probably not have existed in regions where seismic hazard dictates rigorous building codes and increased professional awareness among designers and constructors.

INTRODUCTION

A main goal in the design of any structure is to achieve a level of structural reliability corresponding to the socio-economic importance of the project. Minimum standards criteria set by code authorities [1], and recommendations by research committees [2] ensure that some minimum performance level is met by the structure.

One of the most important demands of any reliability analysis is to define feasible loading conditions, including severities, and probabilities of occurrence. Each additional significant load included in the design will likely increase costs of the final project, since additional strength requirements lead to increased structural member sizes and more elaborate details. Obviously, structures designed to meet modern seismic requirements simply cost more.

The specific lateral and vertical loads, imposed on a structure by earthquake excitation, usually control some aspect of structural strength. However, even in cases where wind pressure conditions govern lateral design of the structure, certain provisions, associated with the cyclic character of seismic loadings, are introduced in the design, particularly where structural details are concerned.

It is often argued that the additional cost increases engendered by seismic design requirements offset the benefits which can be "enjoyed" only in event of a significant earthquake. However, other diverse advantages in

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overall structural reliability gained from the seismic design must also be acknowledged. In particular, the reduction in probability of failure due to seismic event is accompanied by a corollary escalation in structural defense against distress from other causes.

DEFINITION OF FAILURE

Different levels of structural damage and economic loss can be associated with the threshold value used to define failure. Moreover, structural failures can be divided into various categories based on consequential damages as follows:

- Catastrophic failure with loss of life. These events represent the major concern of structural codes and regulations, and a maximum effort has to be made to avoid them. Although recent major structural failures in the United States have resulted in about 200 fatalities and over $1 billion in claimed property damage, these figures should be viewed within the perspective of 50,000 deaths due to traffic accidents, and costs of $300 billion in new construction per year [3].

- Catastrophic failure in which no human lives are endangered. These upsets provoke major economic impact, such as shut-down of vital utility facilities, interruption of communication systems, and damage requiring demolition of a structure.

- Failure resulting in extensive property damage. Here, failures with economically-feasible repairs are represented by instances of cracking that reduce normal design load-carrying capacity, extensive architectural damage (weather tightness loss in windows, cladding, and roof), and damage to the utility supply (air-conditioning ducts, and plumbing).

- Failure resulting in reduced serviceability. Often this type of failure is marked as minor or even cosmetic, having nuisance value, in the case of residential, commercial or industrial buildings, to occupants because of unaesthetic appearance, noisy floors, poor drainage, etc.

ALLOCATION OF FAILURE

Refs. [4] through [7] list major contributions to the understanding of structural failure statistics and distributions. Although limited in number, these studies allow certain conclusions to be drawn as to tributory causes and their importance.

Figure 1 identifies the major sources of structural failures in a very plastic way. The sloped lines indicate failure due to lack of communication between two different stages in the design/construction/usage process. The horizontal lines indicate single stage failure initiation. It can be observed that the greatest number of failures result from errors committed in design stages of the project, followed by communication failures between architect/designer and contractor.

Figure 2 presents the identifiable source of weakness in human performance, which promotes structural failure. Lack of experience followed by inadequate education, lack of ability to approach the technical problems and plain negligence account for the majority of cases.

Table 1 shows the distribution of failures with respect to type of construction. As shown, the majority of failures occur in building type structures; thus, it is probable that most of the reported casualties are due to localized or small collapses and not to massive, dramatic failures.

Figure 3 was prepared based on information provided in Ref. 7. The display presents the alleged allocation of errors which led to failures. The overlap between design and construction phases indicates that, in some cases, errors in both activities were introduced, or that no clear agreement was reached as to source of the main tributory error.

INCREASED RELIABILITY IN SEISMIC DESIGN

Structural reliability includes a wide range of issues with some of the more major ones being: a) definition of loading, b) definition of strength, c) energy absorbtion capability, d) material properties, e) human performance in design, f) construction practices, and g) quality assurance.

Items (b), (c), (f) and (g) are influenced positively by the introduction of earthquake engineering to the design and construction process. With the increased level of sophistication consonant to structural strength analysis of even single-family dwellings in seismic zones [8], reliability of the definition for strength [Item (b)] is enhanced dramatically. Guidelines, such as those presented in Ref. 8, provide assistance toward proper definition of seismic forces and identification of the resisting system, and promote a thorough understanding of lateral and vertical integrity of structural systems.

The recent damaging earthquake which struck the town of Coalinga in Southern California (May, 1983) provided yet another lesson regarding the impact of earthquake engineering on perception of structural integrity. An engineering investigation team lead by the first author of this paper observed different levels of non-earthquake related prior distress experienced by numerous structures. Relatively minor settlements and normal temperature stresses resulted in extensive cracking of the structures. Although not of major importance to non-seismic load resistance, these damages lent an aesthetically unacceptable appearance to the buildings involved. On the other hand, buildings with proper structural tying and an adequate shear resistance system not only resisted the earthquake motion very well, but also did not manifest signs of past distress resulting from other causes.

The concept of energy absorption capability has been introduced to civil engineering practice almost entirely by earthquake engineering developments. For example, understanding of ductile vs. brittle behavior in structural failure which is inherent to this concept not only influences the structural design of special structures having socio-economic importance such as nuclear power plants [9] and offshore drilling structures [10], but also of conventional edifices such as low and high rise buildings [11].

Ref. 10 states that "earthquake ground motion requires more complicated dynamic analysis procedures." The same trend toward engineering sophistication is seen in the development of SEAOC "Lateral Force Requirements" [2]. Requirements of this type probably constitute the most efficient means for clarifying the channel between release of research information and practical application of results therefrom. With more knowledgeable structural analysis techniques being employed, the probability of failure decreases unless human error is involved [9]. In complementary fashion, quality assurance requirements become more stringent as technical competence of personnel involved in the design and construction supervision process increases.

Recent collapse of a reinforced concrete flat slab condominium structure in Florida revealed severe violations of Items (e), (f), and (g), listed previously. A civil engineer, with many years of non-structural work, assumed the responsibility for designing a multi-story reinforced concrete building. Errors in load definition and structural analysis prevailed throughout the project. The designer did not perform a shear punch check which was the eventual mode of failure for the structure. In the process of construction, through excessive concrete cover, the effective slab depth was decreased, contributing to inevitable collapse. Thorough study of accident site photographs revealed additional major deficiencies in construction; for example, congestion of column reinforcement in crossing the slab creating voids in the concrete; and uneven reinforcement distribution in the column perimeter. Despite such abuses, the structure, some time prior to its collapse, gave warning signals of the distress in terms of cracking. Unfortunately, the building inspector ignored those signals, and without a reasonable level of engineering investigation, considered them to be normal and acceptable.

In the Florida collapse, several violations of acceptable human performance in design, standard construction practice, and quality assurance were committed. The relevant questions which arise are:

1. Are the intellectual design requirements associated with earthquake performance of a multi-story reinforced concrete structure in a seismic zone so demanding as to ensure a level of engineering competence that would preclude basic technical errors in execution?

2. Would not the minimal quality assurance control, which is an integral part of earthquake resistant design and construction, preclude construction at such low quality levels?

3. Would cracks appearing in vicinity of the slab column supports not alert an engineer with seismic design background to, at very least, the compromise of structural integrity for the structure?

4. Would detailing of ductile reinforced concrete connections as outlined in SEAOC Recommendations, Ref. 2, result in proper tying between the slab and the columns, to eliminate failure and/or change the pattern of an inevitable failure from one of disastrous collapse to controlled sagging and cracking?

To answer these questions in a positive vein, there must be assurance that the imposition of seismic design regulations, combined with additional and continuous education of the engineering community, will repress negligent design practice. The best averment that these goals can be accomplished will result from a total commitment of the engineering profession itself and not by artificially imposed administrative regulations.

The higher awareness of engineers and contractors toward the necessity of assuring structural integrity and continuity for projects located in seismic zones results in more serious acknowledgement of distress signals. An old, multistory building in San Francisco developed numerous cracks in the walls due to foundation movements caused by nearby excavations. The seemingly small cracks alarmed the consulting engineer as to their impact on seismic integrity of the structure. Indeed, the cracking resulted in loss of continuity between one of the exterior walls and the two main perpendicular side walls. Consequently, the sole lateral support to the wall was provided by ties with the floor. Closer investigation of the structural system lead to additional tying of the floor-wall system, and increase in strength of the floor diaphragm.

Many disastrous failures occur during the construction stage where, very often, accidental loads are experienced by the structure. These loads can result from non-uniform distribution of construction materials being stored, faulty construction sequence, or incorrect equipment handling. Vertical failure of the temporary supporting system is a typical result of these defaults. Closer investigation of such failures reveals that in many instances, additional lateral bracing of the shoring system could have prevented collapse.

Recently, catastrophic failure took place during construction of a concrete highway bridge in a non-seismic zone. Neither the design engineers nor contractors were located in seismic zones. Investigation of the collapse by the present authors revealed a complete disregard for stability of the shoring system. Formwork of the structure was supported by 20 m (60 feet) tall free standing truss towers and no system of resistance to lateral loads was introduced in the shoring scheme other than the intrinsic stiffness of the towers themselves. It is interesting to compare this cavalier practice with that of California bridge and highway construction. Specifically, extensive bracing and cross tying between shoring towers of similar type constitute an integral part of highway ramp and bridge construction in California.

A recounting of this accident does not imply that seismic design standards should be imposed in non-seismic zone construction. Rather, the intent is to focus on benefits associated with awareness that lateral stability of any formwork supporting system, is mandatory even though the structure involved is only temporary.

An antithetical result characterized collapse of a wooden-truss roof system in California. Here, an entire row of king post-to-gable connections failed. All of the trusses sagged at the center of their span; however, total collapse was prevented by seismic anchorage of the trusses to supporting walls; a very clear side benefit of seismic code application.

CONCLUSIONS

- Seismic codes and recommendations provide an important link between the research and design community and the construction industry.
- Seismic education increases awareness and understanding of the structural integrity concept.
- Although not directly transferable to life and dollar values, seismic codes contribute benefits to society over and beyond the earthquake reliability of structures affected.

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TABLE 1
Failure distribution to type of construction [6].

Types of Structures	% of the 692 cases of failure	% of the sum of the damage costs of the 692 cases	% of the 60 cases with injured persons	% of the 60 cases with persons killed
Buildings (housing, office bldgs., etc.)	52	30	37	40
Industrial buildings	22	31	12	8
Highway construction (bridges, tunnels, etc.)	11	32	40	37
Hydraulinc construction (pipe lines, sewage, etc.)	7	4	7	7
Fall out shelters	2	1	2	0
Unknown	6	2	2	8

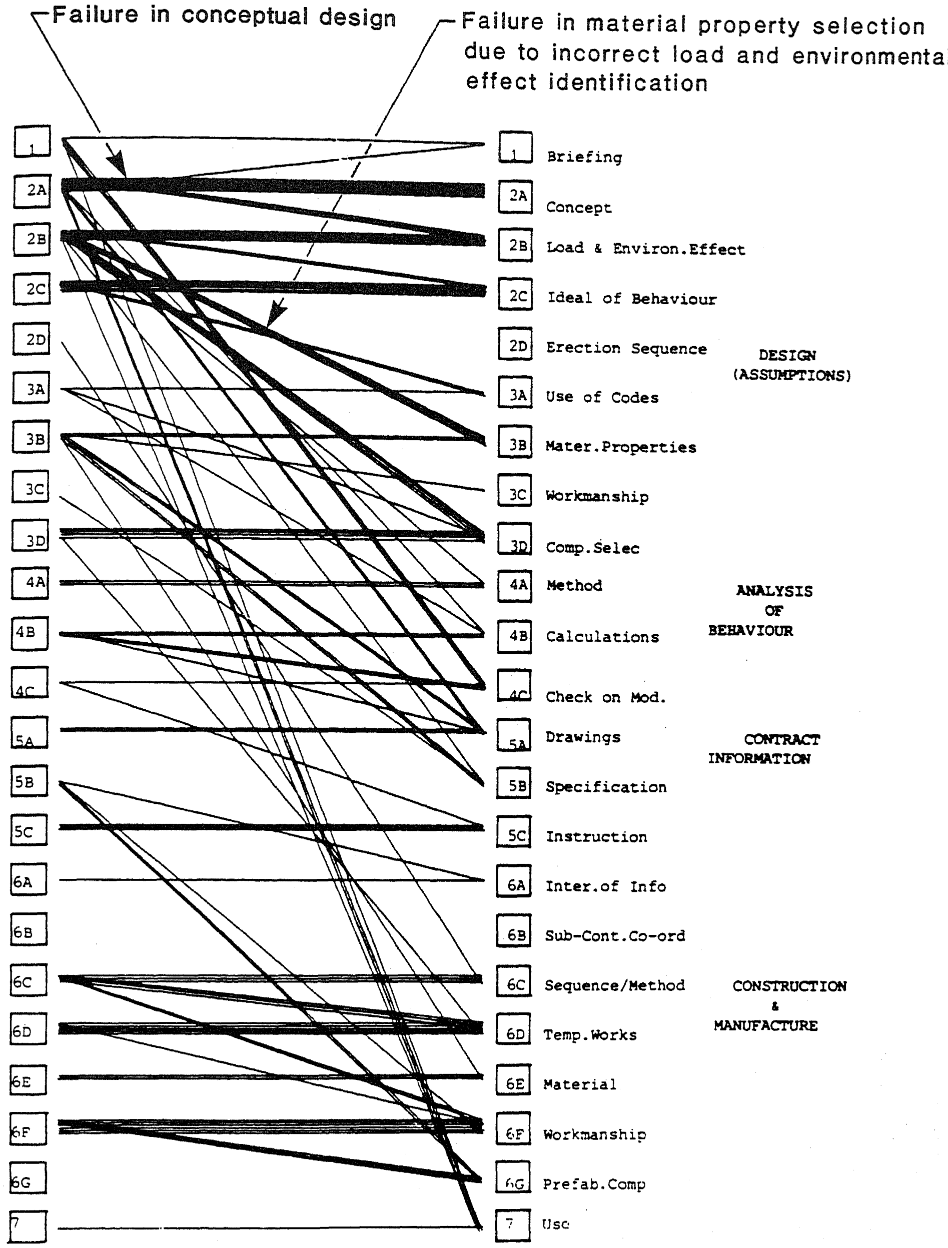

Figure 1. Main failure initiation sources (after Ref. 4)

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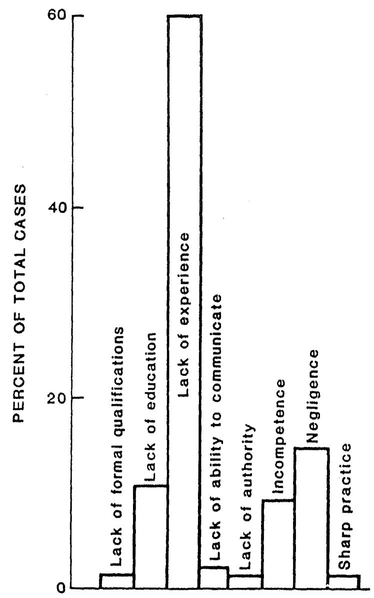

Figure 2. Source of fatal weakness in the designer/contractor/user system [4].

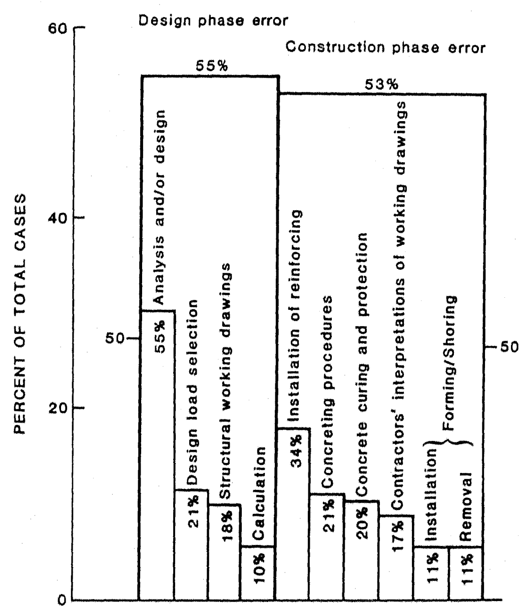

Figure 3. Distribution of error source in design/construction of R/C structures (200 cases data base, after Ref. 7).