LIMIT STATE DESIGN OF MASONRY IN THE UNITED STATES

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ABSTRACT The historical background and the basic policy decisions which were made in the development of a strength design standard are documented. This includes the equations for nominal design strengths, design loads and strength reduction factors.

1. INTRODUCTION

The International Conference of Building Officials has accepted Technical Report No. 4115 (1) which recognizes the use of a strength design approach for the design of one to four story concrete masonry buildings. The purpose of this paper is to document the development and evaluation process that led to this strength design technical report and to describe the fundamental concepts of the strength design approach.

The first section of the paper is a description of the historical background and the fundamental philosophical decisions that were made during the initial work of codifying the strength design approach. Subsequent sections describe technical decisions that were made regarding specific design recommendations for the loading, design strength, nominal strength and strength/serviceability sections of the report.

2. HISTORY OF STRENGTH DESIGN DEVELOPMENT

In 1979, at the request of the Concrete Masonry Association of California and Nevada (CMACN), the two senior authors were asked to evaluate the existing Uniform Building Code (UBC) provisions for the design of reinforced concrete masonry. Of special importance were the provisions related to earthquake design. The resulting evaluation expressed our professional opinion that major revisions were needed in the masonry chapter of the UBC to reflect significant technical and philosophical developments that had occurred since the UBC had been written. The changes were proposed to improve the life safety protection offered by the Code and also to reduce, where appropriate, unwarranted levels of conservatism and, hence, unwarranted construction costs. Our report recommended that CMACN undertake a five-year, three-phase program to bring about these changes. The three proposed phases were:
2.1 Technical/Professional Material

Basic technical material was needed to build a strong foundation for future communication between interested professionals and building officials involved in the modification of the reinforced concrete masonry design approach. A lack of undergraduate training at most universities coupled with a lack of adequate textbook material that incorporated recent technical developments in masonry research made it very difficult for engineers to have a common basis of vocabulary for discussion and theoretical understanding of available design approaches. Subsequent work during this phase resulted in two textbooks that were published by Prentice-Hall (2,3) as well as the publication of material in various professional publications.

2.2 Professional Design Seminars

We believed that the concrete masonry industry should also sponsor series of professional seminars to communicate the progress being made in the development of alternative design approaches. Additionally, a forum would be provided for discussion and the interchange of ideas amongst an audience of practicing engineers and building officials. Ten professional engineering seminars, with a total attendance of over 1500, have been offered by CMACN to achieve these objectives.

2.3 Professional Design Recommendations for ICBO Consideration

Our review of the existing UBC concrete masonry code provisions led us to the conclusion that the current working stress approach to design should be replaced with a strength design approach. The history of the introduction of a strength design approach for reinforced concrete construction suggested that a strength design approach for reinforced concrete masonry would start first as an alternative to working stress design. Eventually, it would become the primary design approach with working stress design retained as an alternative method. To move in the direction of accomplishing this objective, we proposed the development of a strength design methodology for submission to ICBO for review and, potentially, eventual adoption. This design methodology would be presented in acceptable code-related language and would be accompanied by a commentary. The latter would enable engineers and others to understand the philosophical motivation behind major strength design provisions and to evaluate the relative merits of both the proposed and the existing concrete masonry design methods.

In April 1980, the Board of Directors of CMACN unanimously accepted our recommendations but shortened the schedule of the initial scope of work from five to four years. Today, recognition of the significant progress made in the development of the strength design approach and the presence now of a strong theoretical background to support the specific design recommendations contained in the technical report has built confidence in the professional engineering community that concrete masonry structures can be designed safely and economically using strength design.
3. FUNDAMENTAL ENGINEERING DECISIONS

To facilitate the transition from working stress design to strength design in concrete masonry, several fundamental decisions were required. These decisions represented basic policy, the restrictions and preconditions that must be met when using the strength design approach. The philosophy behind these decisions was to ensure that reinforced concrete masonry construction, if it is to be accepted as an engineering material suitable for use with strength design, translates the ideas and concepts expressed in the structural engineering plans to the constructed product in a manner that is both reliable and professional.

The following items are the fundamental preconditions that must be met prior to the use of ICBO Technical Report 4115:

3.1 Reinforced Masonry

The technical report applies the strength design approach only to the design of reinforced concrete masonry structures. This does not imply that the strength design method is inappropriate for the design of unreinforced concrete masonry structures. However, our intent was to focus, as a first step, on reinforced concrete masonry because of its extensive use in the seismic zones of the United States.

3.2 Special Inspection

Technical Report 4115 requires special inspection, as defined in the Uniform Building Code, for the purpose of providing greater quality control over the constructed product. Many hours of discussion took place regarding the cost effectiveness and relative benefits of special inspection. The decision to require special inspection is intended to recognize the beneficial contributions that are made by most inspectors in addition to providing an incentive for the widespread use of special inspection in the concrete masonry construction.

3.3 Vibration/Consolidation

There is clear physical and analytical evidence, as a result of the research conducted during the past decade, that shows that the structural reliability and the strength of concrete masonry is significantly enhanced when the grout in the cells is either vibrated, using a mechanical vibrator, or consolidated with an admixture. Therefore, we believe that the improved reliability and strength of concrete masonry achieved through the use of vibration justifies the additional expense, if any.

3.4 Prism Testing

Prism tests are required as part of the strength design approach because ultimate compressive strength represents an important design parameter. This design variable is utilized in many of the concrete masonry structural design equations to quantify the capacity of the masonry to resist various failure modes.
3.5 Restriction to One to Four Story Buildings

This restriction is somewhat arbitrary and is not really based on known theoretical or practical shortcomings of strength design. It is, rather, essentially a political decision. It resulted from the opinion of a group of respected structural engineers that a prudent first step for the introduction of a strength design approach would be to limit its use to one to four story buildings. Since this restriction eliminates less than two percent of the total concrete masonry construction market, we believed that it had some merit and recommended its incorporation into the strength design approach. Current work involves the development of modifications to ICBO Technical Report 4115 that are intended to enable the report to be utilized for taller structures.

4. MECHANICS OF USE/DOCUMENTATION

In addition to the development of a comprehensive technical and theoretical foundation for strength design, an important practical aspect was the format that the document should have so that the information was clearly presented and easy to use by the practicing engineer. To accomplish this, the ICBO Technical Report requires that a report prepared by Englekirk and Hart Consulting Engineers, Inc. (4) be used to document the strength design approach. Only those design requirements that differ from current UBC Code requirements in Section 2417 are presented in the Englekirk and Hart, Inc. report. This method quickly highlights the differences between the two documents and limits the bulk of the technical report.

The strength design approach detailed in ICBO Technical Report 4115 may be used in lieu of Section 2417 of the 1982 Uniform Building Code. The remaining sections of Chapter 24 still apply. In addition to the design provisions, we believed that a commentary (5) was essential to explain the philosophy and background of each part of the strength design document. This enables practicing engineers to evaluate our logic and approach and suggest constructive modifications where necessary. Both the commentary in the technical report and Volumes 1 and 2 of the Prentice-Hall series provide a basis for review, discussion and modification.

5. LOADING/REQUIRED STRENGTH

The first step we undertook in the development of the strength design approach for concrete masonry was a review of available load factors and loading combinations. Existing concrete masonry working stress design utilizes essentially no load factors. Inasmuch as strength design requires the use of factored loads, a fundamental decision regarding the selection of appropriate load factors and loading combinations had to be made. We reviewed the existing load factors and loading combinations contained in current publications of the International Conference of Building Officials (ICBO), the American Concrete Institute (ACI) and the American Institute of Steel Construction (AISC) as well as a set of proposed load factors then under review by the American National Standards Institute (ANSI). After reviewing these, it was clear that ANSI A58.1-1982 was the appropriate choice of load factors and loading combinations for use in concrete masonry strength design.
The ANSI load factors and loading combinations are based more than over a decade of extremely well documented, high quality research. During their development, and prior to their adoption, the basic research and the final recommendations were subjected to continual, careful scrutiny and review by qualified theoreticians and practicing professionals. These new load factors and loading combinations represent a fundamental and important contribution to the introduction of a rational technical basis for all future loading criteria development. After members of our staff and the authors critically reviewed the documentation and recommendations, we concluded that the ANSI load factors were the essential element to act as a foundation for strength design in concrete masonry.

The source for establishing the loads themselves, D=dead load, E=earthquake load, etc., that are multiplied by the load factors, required another basic decision to be made. We wished to utilize, as much as possible, the appropriate sections of the existing UBC. Thus, the loading criteria in the technical report are those specified in Chapter 23 of UBC. The UBC loads differ only in minor respects from the ANSI loads and, in our professional opinion, are satisfactory at this time.

A more difficult problem to resolve was whether to utilize the existing UBC seismic zone map. The Applied Technology Council (ATC) Report ATC-3-06 presented a seismic zoning map for the United States that was more rationally developed and is probably more accurate than the existing UBC map. In addition, the ATC values provided the basic calibration for the ANSI load factors for seismic forces. The use of the UBC map values would introduce certain theoretical inconsistencies when calculating earthquake forces because the ATC and UBC maps were not developed using the same probabilistic criteria. For example, buildings placed in different areas of seismic risk by the ATC and UBC maps could be designed for either higher or lower levels of structural reliability than that required for other geographic areas. While our natural inclination was to utilize the ATC seismic zoning map, we believed that to undertake the replacement of the seismic zoning map in UBC represented a task which, while worthwhile, was one better left to others. Therefore, the earthquake loads utilized are the UBC earthquake loads along with the associated map. The reader should recognize that improvement in this area will, in all probability, be forthcoming in the next few years.

The expertise necessary to conduct site-dependent special studies for earthquake and wind forces is readily available. The engineer can obtain more realistic estimates of earthquake response spectra from qualified geotechnical engineers while specially tailored wind tunnel studies can provide detailed wind pressure and force determinations. The reasons for not conducting these studies are usually financial and due to the limited scope of the project or budgetary considerations. It is our opinion that such studies should be performed on many more structures in the one to four story building category. Therefore, to provide a mechanism for the inclusion of such studies, a section in the technical report enables the practicing professional engineer to replace the UBC load factors and loads with the results of a special seismic or wind tunnel study.
6. DESIGN STRENGTH

The fundamental goal of strength design, like that of working stress design, is to provide an in-place member strength greater than that required to resist anticipated loads. This relationship may be expressed as

\[(\text{Design strength or resistance}) \geq (\text{Effect of design load})\]

This implies that the real strength of a member must be at least equal to the task of resisting the effects of the applied design loads. The estimate of member strength, commonly referred to as the nominal strength of the member \((V_n, M_n, P_n)\), is the strength calculated using accepted analytical procedures. A strength reduction factor, or \(\phi\)-factor, is used to modify the nominal strength to obtain the strength of the member used for comparison with the load effect.

It is virtually impossible to calculate a zero probability of structural failure because there is uncertainty associated with most aspects of structural design and the construction process. Structural engineers cannot establish, with certainty, the maximum loads that a structure will be subjected to during its design life. Also, reinforcing steel is not always placed exactly as shown on the construction documents. Yet, structural engineers must design buildings in the face of this uncertainty and attain a final level of calculated risk that is acceptable to society.

A portion of the results of the research conducted during the development of the ANSI load factors established levels of structural reliability for a variety of construction materials under different loading conditions. These levels of reliability constitute an implicitly recognized level of acceptable risk on the part of society. Using this information, we developed and calibrated a set of strength reduction factors that reflect this level of acceptable risk.

Factors affecting the value of \(\phi\) include uncertainties in the workmanship, the difference between design loads and expected maximum loads during the life of a structure, the material strength, the physical dimensions and the failure mode. The last consideration is very important because it is usually desirable to provide greater reliability when dealing with brittle modes of failure. The collapse of a column, occurring as the result of the brittle compressive failure of the masonry, is less desirable than the ductile yielding of the tension steel in an under-reinforced flexural member. Thus, it is reasonable that a lower value of strength reduction factor, that is, a more conservative factor, be used for columns than that used for beams.

Another conclusion of the ANSI research was that the current use of one \(\phi\)-factor for all types of modes of failure, i.e. shear in beams versus shear in squat shear walls, does not necessarily result in the desired uniformity in levels of structural reliability. A second finding was that greater uniformity in structural reliability could be attained through the use of partial strength reduction factors. These factors would apply to each material of construction in a member, i.e., concrete masonry and reinforcing steel, and each failure mode instead of the blanket \(\phi\)-factors currently used. The strength design approach for concrete masonry recog-
nized by ICBO has attempted to provide for these refinements by placing the specified strength reduction factor adjacent to the equation to which it applies and by specifying different $\phi$-factors for different types of failure modes in different types of members.

7. NOMINAL STRENGTH

The area that consumed the majority of effort in the production of the strength design approach for concrete masonry was the development of the equations used to calculate the nominal strength. Equations had to be developed for axial, flexure, bearing and shear for the various types of structural members encountered in structural design such as columns, lintels, bearing walls and shear walls.

For axially loaded members, the design formulation is similar to the one used for reinforced concrete. The maximum axial capacity of a column is limited to 80 percent of the theoretical capacity based on the effective area of the concrete masonry and steel. This accounts for the effects of accidental eccentricities present in many axially loaded members. The reliable compressive strength of the concrete masonry is taken to be 85 percent of the prism strength. This reduction accounts for the discrepancies between prism tests and in situ masonry performance due to differences in rates of loading and test specimen geometry. Using the equations in the research report, interaction curves can be constructed for combined axial and bending loads for members not influenced significantly by slenderness effects.

The design of members loaded in flexure is based on a set of assumptions that were developed to be consistent with available research and the structural mechanics of concrete masonry. As a result of numerous tests, an equivalent rectangular compressive stress distribution based on the work of Whitney was substituted for an actual compressive stress-strain distribution. The maximum, usable, unconfined compressive strain is assumed to equal 0.003. The design of flexural members follows the principles of traditional structural mechanics based on force equilibrium and strain compatibility.

Several problems had to be resolved in order to prepare a usable design standard for walls. The design of concrete masonry walls must consider the effects of axial load, out-of-plane flexure and slenderness. Present working stress design standards recognize the existence of these design parameters but place significant, and often arbitrary, limits on permissible height to thickness ratios and allowable stresses. The strength design standard addresses these design parameters by providing three design approaches for concrete masonry walls depending upon the anticipated loading conditions and wall geometry. The design approaches are an empirical formulation for fairly thick walls with minimal loading eccentricities, a formulation for slender but lightly loaded walls and a formulation for walls that carry a higher axial load but are also subjected to out-of-plane loads.

The empirical approach applies only to walls with height to thickness ratios less than or equal to 36 and when the resultant of the compressive load is in the middle third of the cross section. This method is consistent with the methodology for reinforced concrete walls with similar design
constraints. Minimum wall reinforcing is required. However, increased reinforcing above the minimum is not recognized in the nominal strength that is computed using the empirical design approach.

If the wall has a small axial load, less than 4 percent of $f_{mAe}$, the thin wall research conducted by the Structural Engineers Association of Southern California is used. This approach considers the effects of significant lateral loads and P-Δ. Nominal strengths are calculated based on the general assumptions discussed for plain flexural members as well as second order deflections introduced by the axial loads. The thin wall approach also addresses the effects of serviceability albeit using loads with return periods longer than those that one would associate with true serviceability considerations. The problem of serviceability is addressed through the use of deflection control criteria.

The third approach to designing walls is to consider them to be columns with applied moments. Using the approach developed for traditional columns, interaction curves can be constructed that establish the nominal strength of the walls for various combinations of axial load and moment.

Shear design is divided into two sections and addresses, respectively, the shear found in flexural elements and the shear found in shear walls. Unlike current working stress design standards, both the shear strength provided by the concrete masonry, $V_m$, and the shear strength provided by the reinforcing steel above the specified minimum wall reinforcing $V_s$, are included when estimating the total shear strength of the beam or wall. Current working stress design standards ignore the contribution of the concrete masonry to the total shear strength once the theoretical shear strength of the masonry has been exceeded in the design. Only the reinforcing steel above the specified minimum amount of wall reinforcing is considered in calculating $V_s$ because the values of $V_m$ are based on masonry considered to be reinforced.

The values of the shear strength for both beams and shear walls are based on the $M/Vd$ ratio. This parameter accounts for the variation in shear strength because the stress distribution in the structural member is changed as a result of loading and geometric variations.

8. CONCLUSION

The strength design approach permits the structural engineer to more accurately predict the strength of concrete masonry members and walls. The most practical advantage is that the minimum amount of concrete masonry, steel and grout can be used to resist the design loads. Strength design makes concrete masonry a more economical and competitive building material without jeopardizing either the safety of the building occupants or the investment of the owner.

Concrete masonry that is designed and constructed using the strength design approach results in a superior product because ICBO Technical Report 4115 requires special inspection and either the vibration of grout or the use of an expansive additive when the grout is puddled. These requirements are the foundation for the higher design strengths associated with the strength design approach.
The transition from the working stress approach to the strength design method brings concrete masonry into the mainstream of structural design. Strength design represents a well documented and thoroughly tested approach that has been successfully used for nearly thirty years in the design of concrete structures. It incorporates the latest research in concrete masonry design and, at the same time, retains many of the important, time-tested features that make concrete masonry an effective building material.

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10. REFERENCES


