EVALUATION OF THE APPLICABILITY OF NONLINEAR ANALYSIS TECHNIQUES TO REINFORCED MASONRY WALLS IN NUCLEAR POWER PLANTS

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INTRODUCTION

In response to IE Bulletin 80-11, a total of 10 nuclear power plants have indicated that the energy balance technique has been employed to qualify some reinforced masonry walls in out-of-plane bending. Based on the review of submittals provided by the licensees and all available literature, the Franklin Research Center (FRC) staff and FRC consultants have concluded that the available data in the literature is not sufficient to warrant the use of nonlinear analysis techniques to predict the response of masonry walls under cyclic, fully reversed dynamic loading. As a result, a meeting with representatives of the affected plants was held at the NRC on November 3, 1982 so that the NRC, FRC staff and FRC consultants could explain their concern regarding the applicability of the energy balance technique to masonry walls in nuclear power plants [1]. In a subsequent meeting on January 20, 1983, consultants of utility companies presented their rebuttals [2] and requested that they should be treated on a plant-by-plant basis. In accordance with their requests, the NRC staff started the process of evaluating each plant on an individual basis. In this process, the NRC, FRC staff and consultants visited a few nuclear power plants to examine the field conditions of reinforced masonry walls in the plants and to gain first-hand knowledge of how the energy balance technique is applied to actual walls. Key calculations were reviewed with regard to the energy balance technique.

EVALUATION OF ENERGY BALANCE TECHNIQUE

Based on a review of the submittals provided by the licensees, specific plant visits, evaluation of typical design computations and review of all available literature, it is concluded that the concerns raised by the Franklin Research Center (FRC) staff and consultants pertaining to the use of energy balance technique have not been resolved. A summary of these concerns are listed below:

1. Only a few isolated tests have been reported on the lateral resistance of reinforced concrete block and brick masonry walls in out-of-plane bending. Th se tests can be summarized as follows:

(i) Tests have been conducted on 20' high reinforced concrete block walls 8" thick in running bond and stack bond configurations by Dickey and Mackintosh [3]. These tests, although limited, revealed that, under monotonically increasing load, some of the panels failed in a brittle mode prior to reaching yield and that the stack bond was less effective than the running bond.

(ii) More recent tests conducted by the ACI-SEASC Task Committee on Slender Walls [4] on face loaded 24' high reinforced masonry walls under monotonically increasing load showed relatively low ductility ratios in the 3 panels that attained failure. Two 6" nominal fully grouted concrete masonry walls attained ductility ratios of approximately 2 when they failed inadvertently in compression. One 6" hollow brick wall tested to failure also attained a ductility ratio of approximately 2. It has been noted that walls tested were fully grouted and have high steel percentages (0.22% to 0.37%).

(iii) Tests conducted by Scrivener [5,6] on face loaded reinforced masonry walls made of 4 1/4" reinforcing brick revealed high ductilities. The one cyclicallly loaded panel whose load-deflection results are reported [5] revealed very peculiar hysteretic behavior unlike the required elasto-plastic behavior needed for application of the energy balance technique.

(iv) Tests on small masonry structures resulting from an assembly of various components to form single story masonry homes have been carried out at the UC, Berkeley earthquake simulator [7]-[9]. The main objective was to provide design recommendations on the minimum reinforcement required for masonry housing in seismic zone 2. These are the only tests of reinforced masonry walls under realisitc earthquake loads. The reinforced walls tested under out-of-plane bending in this program did not yield under the applied loads. In addition, these walls did not have the boundary conditions of typical applications of masonry walls in nuclear power plants.

(v) Dynamic tests on slender reinforced block masonry walls have been conducted at the EERC, University of California, Berkeley for Bechtel Power Corporation. The program has been conducted to demonstrate the conservatism of the nonlinear dynamic analysis performed by Computech Engineering Services for the masonry walls in the San Onofre Nuclear Generating Station, Unit 1 (SONGS-1). The FRC staff and consultants witnessed one of the tests. It was shown that the wall was capable of resisting significant inelastic deformations when subjected to earthquake input motion. It has to be mentioned, however, that the few tests performed were plant specific and aimed at verifying the conservatism of the nonlinear dynamic analysis technique developed by Computech Engineering Services. Consequently, the parameters included in the program were limited to "as built" condition of the walls in SONGS-1. The program objective was not to verify the use of the energy balance technique.

The above tests that have been conducted on reinforced masonry walls and which are relevant to the evaluation of concrete masonry walls in nuclear power plants do not form a sufficient data base to warrant the use of the energy balance technique.

2. A Technical Coordinating Committee for Masonry Research (TCCMAR) has been formed under the auspises of the US-Japan Cooperative Research Program. It is a recognition of the urgent need for research in the area of seismic resistance of masonry. The committee met in Pasadena in February 1984 to assess the current state of knowledge and to outline an experimental program to provide the necessary data. It has been concluded that the current state-of-the-art of masonry has not progressed enough to

warrant inelastic analysis methodology of masonry structures [11]. A comprehensive test program was recommended. This significant undertaking is a clear indication of the lack of test data available for masonry. (Note: Dr. Hamid serves as a member of TCCMAR.)

3. A large number of variables exist in the construction of concrete block walls used in nuclear power plants. For example, the walls can be fully grouted, partially grouted, stack bond, running bond, single and multiple wythes with different block sizes ranging from 4" to 12" in width. No adequate test data exist in the literature to enable a clear understanding of the effects of these variables on the dynamic fully reversed cyclic behavior of masonry walls.

4. Effects of cut-outs and eccentric loads due to attachments on reinforced concrete masonry walls of the type used in nuclear power plants have not been evaluated experimentally. This type of information, when available, will help to substantiate the various assumptions made in the analysis of such safety related walls.

5. The limited tests that have been conducted and summarized in item 1 above have pointed out to the inability to preclude brittle type failures with low ductility ratios on face loaded panels under monotonically increasing load. A lack of knowledge exists on the maximum attainable compressive strains in the face shell of reinforced concrete masonry walls under out-of-plane bending. This is particularly true under cyclic dynamic loading.

6. In examining the available test data, it is also obvious that there is a significant lack of information about the post-yield envelope and established cyclic load characteristics for reinforced concrete masonry walls under out-of-plane bending which is essential to demonstrate the stable ductile behavior required for the applicability of the energy balance technique. This is attributed to the fact that most tests were not conducted to ultimate failure which is essential for the determination of the post-yield envelope. This deficiency exists for all of the types of masonry construction used in nuclear power plants [10].

7. Some walls are qualified based on one-way bending in the horizontal direction or two-way plate action. These walls are horizontally reinforced with joint reinforcement embedded in the mortar joints every course or every other course. This type of steel is a high tensile steel with a yield stress as high as 100,000 psi indicating a very limited ductility. Masonry codes are not specific about the usefullness of joint reinforcement, particularly in seismic areas [12,13]. If joint reinforcement is to be used to resist tensile stresses, the WSD method should be employed with an allowable steel stress limited to 30,000 psi. The only code [14] that addresses the use of joint reinforcement in seismic areas for categoriees C and D structures was developed by the Applied Technology Council. This code does not allow the use of joint reinforcement as a load carrying element for these two categories.. Safety-related masonry walls in nuclear power plants would fit into these categories. Information about the

cyclic behavior of joint reinforced masonry walls is not available in the masonry literature at the present time [12,13].

8. The energy balance technique has been originally developed as an approximate design tool to check the resistance of ductile concrete and steel frame buildings subjected to seismic loads. With the fast development in computers in recent years, more rigorous nonlinear dynamic analyses of ductile structures have also been made possible.

NONLINEAR ANALYSIS OF MASONRY WALLS

Under seismic loads, strain energy transfer through elastic reponse is very small compared to the inelastic response for energy dissipation. With regard to inelastic behavior, two methods have been used to investigate the dynamic response of concrete and steel structures to a strong motion earthquake. One of the methods requires the formulation of an inelastic model of the structure utilizing the finite element technique. The model is then subjected to time-history ground motion and the dynamic response is determined. The results of this approach, which is time consuming and costly, depends on how accurately the structure is represented by the inelasctic model and how well the material properties are defined. Therefore, a limited confirmatory dynamic test program should be conducted to check the conservatism of the assumptions used.

The other method, which is easier to apply in a design office, separates the properties of the structure from those of the earthquake. The earthquake is represented by a response spectrum which is then modified to accomodate the inelastic or ductile response of the wall [15]. This method which relies on the energy balance technique requires information about ductility and energy absorbtion capability of masonry walls which, as discussed previously, have not been demonstrated experimentally for general applications. A ductility factor of 1 or 1.5 is suggested [16] for damage-level earthquake intensities where as ductilities of 2 to 3 is recommended [16] for use with collapse-level response spectra. Because the energy balance technique is an approximate simplified method, an adequate and more comprehensive data base should be generated to check this design methodology.

TEST PROGRAM RELATED TO ENERGY BALANCE TECHNIQUE

If a confirmatory test program is elected to justify the use of the energy balance technique, it is expected that the test panels should represent the actual configuration, construction details and boundary conditions of masonry walls in nuclear power plants.

The test program should cover the different parameters that would affect wall performance such as steel percentage, bond type, partial grouting and block size.

The test objectives should be centered upon the following:

1. To demonstrate that the masonry walls would maintain their structural and functional integrity when subjected to SSE and other applied loads.

2. To demonstrate that a stable ductile behavior characterized by steel yielding is guaranteed and that any

brittle failure (e.g. crushing) is precluded.

3. To develop necessary information to verify the energy balance technique as a methodology for the qualification of reinforced masonry walls in nuclear power plants.

4. To demonstrate that adequate margins of safety exist for walls subjected to design lateral loads.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A review and evaluation of the available information on the nonlinear behavior of block masonry walls under out-of-plane loading has been presented. It is concluded that test data are needed to substantiate the use of nonlinear analysis techniques to qualify reinforced block walls in nuclear power plants.

To qualify masonry walls based on nonlinear analysis, two alternatives are recommended:

1- Develop rigorous nonlinear time-history analysis techniques capable of capturing the mechanism of the walls under cyclic loads. Different stages of behavior should be accurately modeled: elastic uncracked, elastic cracked and inelastic cracked with yielding of the central rebars. Then, a limited number of dynamic tests (realistic design earthquake motion inputs at top and bottom of the wall) should be conducted to demonstrate the overall conservatism of the analysis results. In this case, "as built" walls should be constructed to duplicate the construction details of a specific plant.

2- Conduct a comprehensive test program to establish the basic nonlinear behavioral characteristics of masonry walls (ie. load-deflection hysteretic behavior, ductility ratios, energy absorbtion and post-yield envelopes) for material properties and construction details pertaining to masonry walls in question. The behavior revealed from the tests should then be compared with that of elastic-perfectly-plastic materials for which the energy balance technique was originally developed. If there are significant differences, then the energy balance technique should be modified to reflect the actual wall behavior.

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