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Strengthening of Masonry Buildings in the United States

Renforcement des bâtiments en maçonnerie aux Etats-Unis

Verstärkung von Backsteinbauwerken in den Vereinigten Staaten

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SUMMARY

Research in the general field of Civil Engineering is supported principally by the National Science Foundation (NSF), an agency of the Federal Government. The broad fields of earthquake engineering research are described in general announcements of the NSF programs and budget descriptions. High among the priority topics listed in the Earthquake Engineering Program is the entire field of risk analysis, repair, strengthening, and evaluation of masonry structures with special emphasis on the seismic behaviour of unreinforced masonry buildings of clay brick and/or concrete block.

RESUME

La recherche dans le domaine général du génie civil est financée essentiellement par la «National Science Foundation» (NSF), un organisme du gouvernement fédéral. Les projets de recherche dans le génie sismique sont décrits de façon générale dans les programmes NSF et dans les budgets correspondants. Parmi les sujets prioritaires mentionnés dans le programme du génie sismique, il y a l'analyse de risque, la réparation, le renforcement et l'inspection des structures en maçonnerie; un accent particulier est mis sur le comportement aux séismes de bâtiments nonrenforcés en maçonnerie de briques en terre cuite ou de blocs en béton.

ZUSAMMENFASSUNG

Die allgemeine Forschung auf dem Gebiet des Bauingenieurwesens wird hauptsächlich von der «National Science Foundation» (NSF) unterstützt, einer Amtsstelle der Bundesbehörden. Die weiten Zweige der von Forschern betriebenen Erdbebenforschung werden in Mitteilungen der NSF-Programme und -Budgetbeschreibungen dargelegt. An vorderer Stelle unter den aufgeführten Themen des Programms für Erdbebenwesen steht das umfassende Gebiet der Risikoanalyse, Reparatur, Verstärkung und Schätzung von Backsteintragwerken mit besonderer Betonung auf das Erdbebenverhalten von unverstärkten Backsteinbauwerken aus Tonziegeln und/oder Betonblöcken.

Research in the general field of Civil Engineering is supported principally by the National Science Foundation (NSF), an agency of the Federal Government. The recipients of the funding support are the university professors and researchers, although we do support some non-profit organizations, such as: the National Academies of Science and Engineering; the Earthquake Engineering Research Institute-the professional society for the earthquake community; the Applied Technology Council-the research organization of the Structural Engineers Association of California; and private professional organizations, such as consulting engineering firms.

The procedure by which the research is supported is the peer review process. This process is based on unsolicited research proposals received from investigators noted above in response to the general objectives of the programs announced by the National Science Foundation.

The proposal is reviewed by experts in the same field as the proposal, and a decision to award or decline is made by the NSF Program Director based mostly on the nature of the review comments. Thus, it is a random process for the selection of specific projects to be supported in any NSF designated discipline, such as the Earthquake Hazard Mitigation Program, in the Division of Civil and Environmental Engineering.

The broad objectives of the Earthquake Engineering Program are to support research projects directed at developing the basic technical knowledge required to mitigate the losses from damaging earthquakes, and to disseminate the acquired information to decision-makers; such as consulting engineers, architects, planners, local, state, and Federal regulatory bodies and agencies, and other related financial organizations and business institutions. The broad fields of earthquake engineering research to be pursued by the researchers are described in general announcements of the NSF programs and budget descriptions.

High among the priority topics listed in the Earthquake Engineering Program is the entire field of risk analysis, repair, strengthening, and evaluation of masonry structures with special emphasis on the seismic behavior of unreinforced masonry buildings of clay brick and/or concrete block.

The greatest risk for loss of lives and property is in the large number of unreinforced masonry buildings which exist in the United States since colonial times. These buildings constitute the largest inventory of hazardous buildings in all regions of the country including the moderate to high risk earthquake zones. As a result, there are many different types of buildings with masonry construction which means that the number of research projects which are required are endless. Because of the unique nature of masonry construction, very little research on their seismic performance had been conducted until the San Fernando earthquake of 1971 brought it to the attention of the earthquake community and the

Federal Government because of the collapse of many masonry buildings. Practically all of the existing buildings were constructed before seismic regulations were instituted and/or enforced. Therefore, in order to strengthen these buildings, it is necessary to develop the appropriate research information which will evaluate the inherent strength of the structure and then to verify various methods for the repair and strengthening of the several structural components such as walls, roofs, floors, and connections of all assemblies. These topics become the basis for the research projects supported by NSF.

One of the important features of the NSF earthquake program is the dissemination of the research results. An effective method has been the support of a North American Masonry Conference periodically (four year intervals) by which researchers present the results of their work to a broad audience and exchange data and information on their projects. The First Conference (1) was held at the University of Colorado, Boulder, Colorado, in 1978, anad the Second one (2) was held at the campus of the University of Maryland at College Park, Maryland.

These Conferences produce a Proceedings of the papers presented and those accepted for publication in order to contain in one volume all the research data which was developed for the time period between Conferences.

By this method, a researcher or designer can easily refer to the Conference Proceedings to learn what is being done and what has been accomplished in the total research field of masonry analysis and construction.

A brief description of the current research projects is presented below with a statement of the objectives and the status of the project at this time.

3. METHODOLOGY FOR MITIGATION OF SEISMIC HAZARDS IN EXISTING UNREINFORCED MASONRY BUILDINGS

This project will develop a methodology for the mitigation of seismic hazards in existing unreinforced masonry buildings to be applied throughout the entire United States because of the various degrees of vulnerability to earthquake damage. The methodology will provide analysis techniques and procedures to determine: degree of seismic hazard, mechanical properties of unreinforced masonry materials and components, requirements for hazard mitigation, and cost-effective methods for repair and strengthening these types of buildings.

The research consists of a combined analytical and experimental investigation which includes: dynamic testing of full scale walls subjected to out-of-plane motions typical of those which would occur in a building at the top and bottom of the wall; and dynamic and static testing of full scale horizontal diaphragms subjected to in-plane loadings. The walls varied from 10 to 16 feet (3.0 to 4.9 m) with height-to-thickness ratios between 14 and 25. The walls were of 3 wythes of common clay brick, grouted and ungrouted concrete block, and grouted clay block. The diaphragms were 20 x 16 feet (6.1 by 19.3 m) and included wood, metal deck, and concrete filled metal deck systems.

The objective of these tests is to correlate the diaphragm response to the resistance against collapse of unreinforced masonry walls subjected to out-of-plane seismic motions. Simplified analytical methods will be developed from this research. As a matter of interest, the results from this investigation contributed significantly to the development of a city ordinance to reduce the earthquake hazard of existing buildings in the city of Los Angeles, California in 1981.

4. BASIC PROPERTIES OF CLAY UNIT MASONRY

The objective of this research is to investigate, in-depth, the factors which control the strength of brick masonry in compression under static and dynamic loading environments. As of April 1, 1983, the following tasks have been accomplished:

1) Triaxial tests of several mortar mixes to develop mortar strength, modulus of elasticity and poisson's ratio for use in a masonry failure analytical model.

2) An apparatus for tensile testing of whole bricks and for use in combined tensile-compressive tests of bricks has been developed. This data is also required for the failure model.

3) A method to reduce the lateral confining friction force exerted on compression specimens has been developed. This is used in compression tests of brick and brick prisms to obtain "unconfined" compressive strengths for use in the failure model. Compression tests of strain-gauged bricks have demonstrated the effectiveness of the interface friction reduction method.

Future work includes experiments of prisms made with different brick-mortar combinations to enable comparisons between theoretical predictions based on the failure model and actual performance, and also includes cyclic compression tests of prisms at rates simulating seismic loadings on the compression of full-scale masonry.

5. AN INVESTIGATION INTO NONDESTRUCTIVE EVALUATION OF MASONRY STRUCTURES

Six nondestructive evaluation (NDE) methods were investigated to assess their potential use for strength and condition evaluation of masonry using unmodified commercially available equipment. The methods were: vibration, rebound hammer, penetration, ultrasonic pulse velocity, mechanical pulse velocity, and acoustic-mechanical pulse. The candidate methods were applied to two-wythe cantilever wall specimens. Companion small-scale specimens, specimens removed from the walls subsequent to the NDE tests, and in-the-wall specimens were tested to destruction to provide compression, shear and flexural strength data for correlation studies. Flaws, in the form of delaminated bed joints were created in the wall specimens to determine the ability of each NDE method to detect defects in masonry.

Measurements from each method except acoustic-mechanical pulse were compared to strength properties as established by destructive tests using bivariate linear regression analyses. Results of the analyses indicate that strength properties of the masonry tested could be generally estimated by some of the NDE methods considered with the highest correlation coefficients in the 0.8 to 0.9 range. Investigation of the acoustic-mechanical pulse method was very limited, but indicated that consistent measurements could be obained and that flaws could be detected.

It was concluded that NDE methods offer a means of relative quality assessment and flaw detection, and with present procedures and equipment, a limited quantitive evaluation of the type of masonry tested. It was also concluded that with refinements of procedure and some modifications to equipment, the efficacy of most of the methods evaluated would be enhanced. Further investigation of the acoustic-mechanical pulse method appears warranted based upon the very limited experience gained and that further studies are needed to assess the utility of NDE for other types of masonry.

6. CYCLIC RESPONSE OF MASONRY ANCHOR BOLTS

This experimental research project is nearing completion in which the strength of "J" bolts embedded in brick and concrete block masonry is determined. The bolts investigated varied in diameter from 3/8" to 1-1/4" and were tested in shear, axial, and combined shear and axial directions. The tests were repeated with monotonic and cyclic loading.

Results indicate that strengths increase with bolt diameter up to the 3/4" size, with little additional benefit from larger sizes. Current code allowables appear to have a safety factor of approximately ten. The results of this research are extremely important to the designers, engineers, and code bodies because very little reliable data was available when most of the currently used values for bolt strengths were established.

7. SEISMIC RESPONSE OF COMPOSITE MASONRY IN NEW AND EXISTING STRUCTURES

This research project assesses the behavior of new and existing composite masonry buildings subjected to static and cyclic loadings using an analytical and experimental approach.

The analytical phase includes the development of a finite element model in the form of a "Superelement" which may be used in the analysis of large and complex composite walls. The "Superelement" includes both wythes and the collar joint, and considers shear failure at the collar joint as well as in-plane failure of each wythe. The emphasis is on the development of criteria for delamination of the interface due to shear stresses caused by the superimposed loads, thermal effects, expansion and shrinkage due to moisture, and creep.

The finite element model for the interface shear strength will be verified by means of static and cyclic tests. The values of constants assumed in the development of the finite element model concerning shear failure will be modified, if necessary, to achieve a better correlation between the analytical and experimental results. The results of this research project will develop criteria for the design of composite masonry walls subjected to in-plane loads.

During the first year of this project, a composite element that is capable of transferring shear under linear elastic conditions was developed. Currently, thermal effects, moisture expansion and contraction, and creep phenomenon are being incorporated into the model. Sixty composite wall specimens, each 16 inches square, constructed with 3/8" thick slushed mortar collar joint have been tested under static and cyclic loads. Variables in these tests were mortar, reinforcement, type of loading, and absorption in brick and block. Specimens with 2 in. collar joints are currently under preparation for continuation of the experimental phase.

8. STRENGTHENING OF BRICK MASONRY WALLS WITH SHOTCRETE

The objectives of this experimental research project on strengthening of existing unreinforced brick walls are four-fold:

(1) Investigate the bond strength between shotcrete and old, molded clay brick and the effect of wetting the brick or coating it with epoxy prior to application of shotcrete; (2) determine the interface shear capacity of the brick-shotcrete composite; (3) determine the need for and influence of steel dowels which anchor two wythes of brick to a surface layer of shotcrete; (4) investigate the possible use of a thick, lightly reinforced layer of shotcrete on one or both sides of a brick wall for seismic strengthening in regions of moderate earthquake risk.

One or two wythe brick panels measuring 1m x 1m and 1.3m x 1.3m were reinforced with a 9cm layer of shotcrete on one side and were tested to determine the overall behavior of the brick-shotcrete system and to determine whether the bond between the brick and shotcrete is sufficient to develop full composite behavior for in-plane loads. The shotcrete (f' = 47.9 MPa) was reinforced with a welded wire fabric, with a reinforcement ratio of 0.0018 in each direction. Some panels were dry prior to shotcreting, others were thoroughly wetted, while some were coated with epoxy. Wall panels were tested under a reversed cycle, in-plane load across the diagonals. Results indicate that similar panels with different surface conditions developed the same strengths but that the wetted and epoxy coated brick panels exhibited greater inelastic deflection capacity and, thus, greater seismic resistance. The shotcreted panels averaged more than thirty times stronger than unstrengthened brick panels. Unreinforced wall panels could not sustain reversed loading.

Reinforcing bar dowels of size number three (10mm diameter) were epoxy bonded into two wythe panels prior to shotcreting. Panels without such dowels demonstrated the same strength as those with dowels but at large reversed cycle deflections. Panels with dowels remained intact while those without dowels delaminated. Some panels were strengthened with a 3.8cm layer of shotcrete reinforced with an expanded metal lath (0.0025 reinforcement ratio). Strengthening of the brick panels was shown to be proportional to the thickness of the shotcrete. Future tests will examine the out-of-plane behavior of 0.7m x 2m panels in order to determine better values for the interface shear resistance.

9. SEISMIC RESISTANCE OF MASONRY PIERS

This research project has the objective of improving the seismic resistance of masonry piers. The investigation consists of experimental and analytical studies. By improving behavior, we mean increase the ability of the pier to sustain deformation and absorb energy before it fails.

The experimental arrangement can be explained briefly. The pier is first subjected to a specified vertical loading using vertical actuators. Then horizontal displacements are imposed cyclically at the top of the pier by means of horizontal actuators. The amplitude is increased monotonically until failure. Combinations of displacements and horizonal forces necessary to realize these displacements are recorded and result in hysteresis loops. The envelope of these loops acts as a measure of the pier's capacity to absorb energy. A recent improvement in the test procedure which prevents rotation at the top of a pier has been achieved by removing restraining rods and coupling the vertical actuator loads to the horizontal displacements.

The method used for increasing seismic resistance of piers depends on whether the pier will demonstrate a flexural or shear failure. Flexural failures will occur when the vertical load is relatively light, that is, at the upper stories of a building. This failure can be improved by reducing the vertical reinforcement and using toe plates to reduce toe crushing. Shear failure (typical x-cracking) occurs when the vertical load is large. Shear failure can be improved by the addition of horizontal reinforcement. The most important aspect of this failure mode is the anchorage of the horizontal bars. Anchor plates at the ends of the bars have dramatically increased the ductile behavior of the walls.

10. BASIC PROPERTIES AND STRENGTH OF CONNECTIONS FOR CONCRETE MASONRY BUILDINGS

The objectives of this project are the determination of the basic properties of concrete masonry units, prisms, and walls, using various mortars, and the strength of connections between walls and floors.

The basic properties of concrete masonry have been determined and published in several journals, such as the First North American Masonry Conference. The investigation of the strength of the conections is in its final stages and publication of the results will be available later in the year.

11. REPAIR OF MASONRY WALLS WITH EPOXIES

This project was recently awarded, therefore, the researcher is just starting his planning for the series of tests which will be performed subsequently. The objective of the investigation is to determine the feasibility of drilling a hole in a one or two story masonry wall, then inserting a reinforcing bar of pre-determined size, and grouting around the bar with standard grout, concrete mixture, and structural epoxy. A cost-benefit study will be made to determine the best method for the repair and/or strengthening of the wall to increase the seismic resistance. There are many masonry buildings of one and two stories in height in the United States which could be preserved by this technique if it is found to be effective, technically and economically.

12. SLENDERNESS RATIOS FOR MASONRY WALLS

The objective of this project, which is completed, was to determine the response of walls with different ratios of height-to-thickness (slenderness ratio) when subjected to eccentric axial forces acting in combination with lateral forces which simulated the condition of gravity loads on the walls with wind or seismic forces in the lateral direction.

A total of thirty full size panels were tested consisting of tilt-up concrete, concrete block, clay brick, and clay blocks. Slenderness ratios of 30 to 60 were investigated by using a special test fixture constructed specially for this project.

A result for one of the walls is the following data. Concrete masonry wall 24 ft., 8 inches high, four feet wide, reinforced with five number four bars of grade 60 steel, block strength of 2600 psi, slenderness ratio of 38, subjected to a vertical load on the wall of 860 pounds per lineal foot and lateral load of 75 pounds per square foot at yield of steel, deflected 6.5 inches and attained a maximum deflection of 11.2 inches.

Similar data for the other tests have been evaluated and the results are being used to formulate building code requirements for consideration by code writing bodies.

It is interesting to note that this project was independently supported by the Structural Engineers Association of Southern California and the Southern California Chapter of the American Concrete Institute.

The National Bureau of Standards (NBS) (13) of the U.S. Department of Commerce has conducted several projects related to the strength, stability, and structural performance of masonry walls and has reported the results in the Structural Journal of the American Society of Civil Engineers and by several NBS publications of the Building Science Series.

Most of the projects noted above have been supported by the National Science Foundation as a part of its Earthquake Hazard Mitigation Program.

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4. Basic Properties of Clay Unit Masonry, Atkinson-Noland and Associates, and University of Colorado, James L. Noland and Daniel P. Abrams, Address: Atkinson-Noland, 2619 Spruce Street, Boulder, CO 80302.

5. An Investigation into Non Destructive Evaluation of Masonry Structures. James L. Noland. Address: see (4).

6. Cyclic Response of Masonry Anchor Bolts, Russell H. Brown, Department of Civil Engineering, Clemson University, Clemson, South Carolina 29631.

7. Seismic Response of Composite Masonry in New and Existing Structures. Russell H. Brown and Subhash Anand, Clemson University - see (6) for address.

8. Strengthening of Brick Masonry Walls with Shotcrete. Lawrence F. Kahn, School of Engineering, Georgia Institute of Technology, Atlanta, GA 30332.

9. Seismic Resisance of Masonry Piers. Hugh D. McNiven, Director-Earthquake Engineering Research Center, 47th and Hoffman Boulevard, Richmond, CA 94804.

10. Basic Properties and Strength of Connections for Concrete Masonry Buildings. Gilbert A. Hegemier, University of California, San Diego, CA 92307.

11. Repair of Masonry Walls with Epoxies. Joseph M. Plecnik, Department of Civil Engineering, North Carolina State University, Raleigh, North Carolina 27607.

12. Slenderness Ratios for Masonry Walls-Structural Engineers Association of Southern California and ACI-Southern California Chapter. Contact: James E. Amrhein, Director of Engineering, Masonry Institute of America, 2550 Beverly Boulevard, Los Angeles, CA 90057.

13. National Bureau of Standards-Contact: Felix Y. Yokel, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C. 20234.

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