The Seismic Retrofitting of Local Clay Block Walls: Research in Progress

R.P. Clarke and A.K. Sharma
Department of Civil Engineering
The University of the West Indies
St. Augustine, Trinidad

Abstract

The Caribbean region is a high risk area with respect to earthquakes. However, the vast majority of buildings, especially the residential structures, have not been designed to withstand earthquakes. This paper discusses research in progress at The University of the West Indies, St. Augustine, on a retrofitting method using ferrocement overlays on the faces of walls built with clay blocks common to the region but particularly to Trinidad and Tobago. Variables include mesh type, number of layers, and vertical pressure. Detailed data on this retrofitting method is scarce and apparently non-existent for clay blocks with horizontal cores such as the local blocks. The approach is to develop a cyclic constitutive model for the walls and, using this information, conduct a study of common low-rise structures via dynamic analysis. The study will culminate in the preparation of design and construction guidelines.

Introduction

The Caribbean region lies in an active seismic zone and forms the Caribbean Loop of the Circumpacific belt. The seismological data for the Caribbean region include historical reports of felt and damaging earthquakes which began about 300 years ago, and instrument data for about the last 80 years.

According to Tomblin (1978), the historical records provide an important extension of the time interval covered by the instrument records but do not form an adequate basis for estimating numerical values such as acceleration, or for accurately identifying the sources of activity. However, the historical records do confirm that most of the early-established towns or cities of the Caribbean borders have suffered at least one devastating earthquake, and that several earthquakes have occurred which, from the extent of destruction (e.g. 650 km from Merida to Caracas in 1912, and 400 km from St. Kitts to St. Lucia in 1843) probably had Richter magnitudes between 8 and 8.75. Differences in the frequency per century of damaging earthquakes, based on the total historical record, range from between 3 and 8 per century for different islands of the Lesser Antilles to 14 in Port of Spain, Trinidad, and 17 in Kingston, Jamaica. The instrument records afford a more precise view of the seismicity of the Caribbean, the salient features of which are therefore indicated in Figures 1 and 2.

There are three basic types of lateral resistive building systems: moment-resisting frames; braced frames, and the box system. The Caribbean region is a Southern region and as such the growth of its cities into metropolises is at an early stage relative to that of the developed countries. As a result, the vast majority of buildings to be found in the Caribbean are low-rise or single-storey where the former is herein defined as being from two to four storeys.

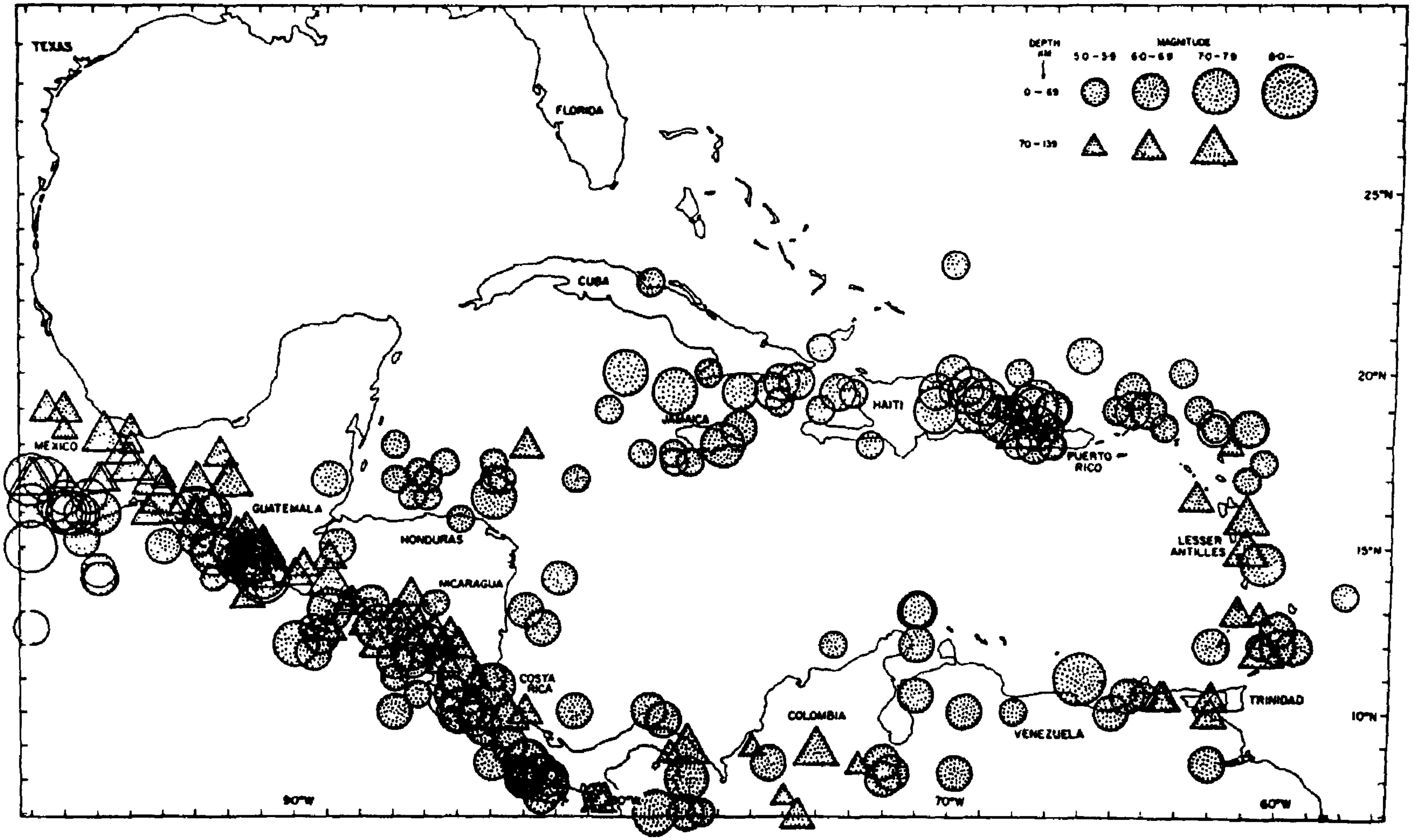

Figure 1: Caribbean earthquake epicentres 1898-1952. (From Shepherd and Aspinall, 1980)

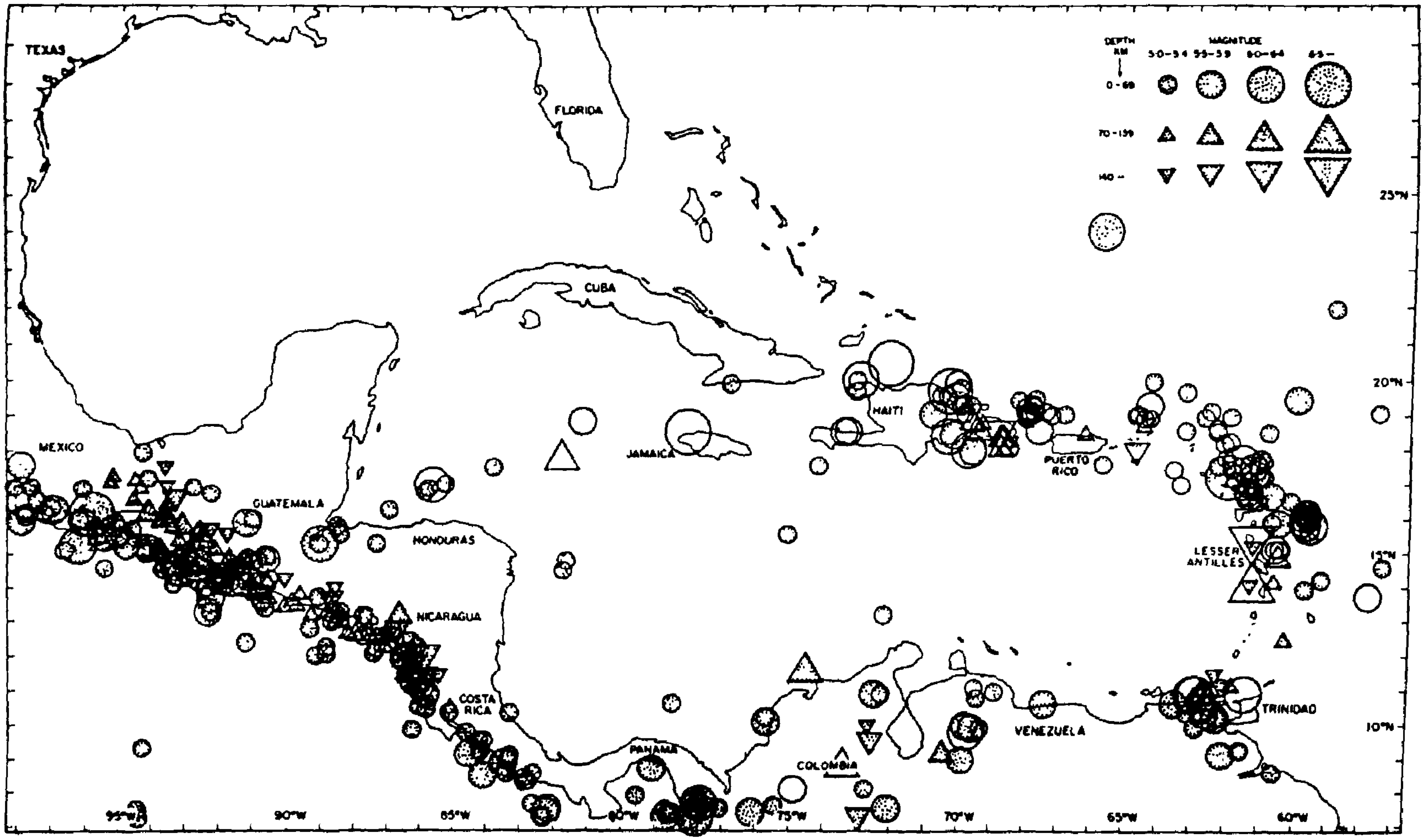

Figure 2: Caribbean earthquakes 1953-1963 (open circles) and 1964-1976 (dotted circles). (From Shepherd and Aspinall, 1980).

The types of lateral resistive systems to be found in the Caribbean's low-rise and single-storey buildings can be roughly broken down as follows in increasing order of occurrence:

a) low-rise box systems
b) low-rise combined systems
c) low-rise moment-resisting frames
d) single-storey industrial moment-resisting frames
e) single-storey industrial combined systems
f) single-storey residential box systems

The single-storey residential box system represents a high percentage of the total above. The materials used for almost all of these low-rise or single-storey systems are: masonry; timber; reinforced concrete; nogging, and adobe. This list is in decreasing order of occurrence with masonry being the most prevalent.

These systems are meant to provide resistance to lateral forces in general. However, with respect to earthquake forces, most of the region's buildings have not been designed in accordance with aseismic design codes or guidelines. This is due to the history of earthquake resistant design in the region. The first attempt to formalise earthquake resistant design recommendations in the Caribbean was made in 1970 by the Seismic Code Committee of the Association of Professional Engineers of Trinidad and Tobago. The recommendations have gone through several phases of refinement since then culminating in the acceptance in 1978 of "The Recommended Lateral Force Requirements and Commentary (1975 edition)" of the Structural Engineers Association of California (SEAOC) as the basis of the revised West Indian Seismic Code. This was incorporated into the Caribbean Uniform Building Code (CARICOM Secretariat, 1985). The latter document has also incorporated suggestions from the Regional Seminar on Earthquake and Wind Engineering which was held in Trinidad in 1983. The recommendation to accept the SEAOC code was made by the Seismic Code Drafting Committee which was formed to review the main points of the First Caribbean Conference on Earthquake Engineering held in 1978.

Nevertheless, although at this time some form of scientific guideline exists, in Trinidad and Tobago as of 1980 for example, forty-seven (47) percent of the private households were built before 1962 and thirty-two (32) percent utilized the box system (Central Statistical Office (1974). Each of the aforementioned materials used in the construction of low-rise structures in the Caribbean has a relatively high number of brittle failure modes. Reinforced concrete can be made sufficiently ductile for medium-rise and even some high-rise buildings but it must be properly detailed and the construction cost for the required ductility may be difficult to justify.

It is probable therefore that a large number of reinforced concrete systems will enter brittle failure modes. The same can also be said of the masonry which even if properly reinforced would still have quite limited ductility. Timber is acknowledged as a good earthquake resistant material primarily due to its high strength-to-weight ratio. However, adequate connections must be provided to ensure proper continuity between structural members so again the issue of the lack of adequate aseismic recommendations implies that such systems will also enter brittle failure modes. The tendency towards brittle failure of the lateral resisting systems in the Caribbean is further accentuated by the fact that such systems are low-rise implying shear or shear-associated deformation modes (as opposed to the flexural mode) which lowers the available ductility.

At the aforementioned 1983 Regional Seminar on Earthquake and Wind Engineering a paper was presented by Faccioli, Taylor and Shepherd entitled, "Recommendatons on the Level of Lateral Forces to be Used for Earthquake Resistant Design in the Caribbean Region". In this paper it was estimated that the magnitude of the maximum probable earthquake in the Caribbean, with the exception of Barbados, be taken as greater than 7.0 Ms. It is reasonable to assume, therefore, that should such an earthquake take place there would be a high risk of collapse of a significant number of residential structures, especially in Trinidad. Considering the occurrence of the maximum probable earthquake in Trinidad, a rough estimate indicates that a minimum anticipated loss would be of the order TT$ 900M. This estimate does not consider damage to public services and furnishings. In addition, the loss of life would probably be in excess of 3,000 people if the earthquake were to occur during usual working hours, but a much larger number is anticipated if it were to occur at night.

Ferrocement - The Material and its Potential For Aseismic Design

Ferrocement is a special type of thin shell reinforced concrete. Typically less than 40 mm in thickness, ferrocement consists of several layers of thin wire mesh of small inter-wire spacing, tied together to form a dense cage and impregnated with cement mortar with very little cover over the reinforcements. Recent developments in ferrocement are such that the term also applies to the use of non-ferrous mesh (such as bamboo) constituting the reinforcements.

The structural behaviour of the resulting composite is such as to warrant its classification as a separate material primarily on account of its relatively high deformation or strain capacity and its apparently synergistic behaviour. The material has been described as being anomalously both the oldest and newest form of reinforced concrete. This is because it is the forerunner (at around 1848) to the common reinforced concrete, passed through a one hundred year period of disinterest, then received considerable attention by Nervi in 1948 for marine applications. Since that time its noteworthiness for terrestrial applications has been amply demonstrated and at present it is receiving such international attention in the areas of low-rise structures (especially housing), roofing, storage structures, and as an integral unit in the formation of hybrid structural elements (with reinforced concrete or masonry for example) as well as mixed structures. A description of some of its many attractive and relevant features is as follows though a very apt summary was recently coined by Al-Sulaimani and Ahmad (1988) as its being the "missing link" between steel and reinforced concrete.

a) High strength-to-weight ratio.
b) High ductility which increases with reinforcement sub-division in the matrix.
c) High degree of quality with little supervision by technical personnel.
d) minimum foreign exchange dependency (i.e. raw materials are readily available)
e) Minimum plant requirements for fabrication.
f) High degree of uniformity.
g) Ease of fabrication of monolithic connections.
h) Orthotropic material properties.
i) Can be cast into almost any shape without formwork.
j) Minimum material wastage by "tailoring" to suit imposed stresses in the design phase.

Given the acknowledged characteristics of a good earthquake resisting material, ferrocement is an excellent candidate for investigation in this area, especially for developing countries.

Though this structural material is relatively young in terms of the number of man-years devoted to its research so far, it is clear that it has considerable potential as a solution to developing countries in particular. This is evidenced by the formation of the International Ferrocement Information Centre (IFIC) in 1976 as a result of recommendations made in 1972 by the U.S. National Academy of Sciences Advisory Committee on Technological Innovation (ACTI); the establishment of Committee 549 by the American Concrete Institute (ACI), and the formation of the International Ferrocement Society (IFS) in 1991.

It appears that to date there has not been any rigorous study of the seismic behaviour of ferrocement. A rigorous study is herein understood as having at least one of the following general characteristics:

i) the derivation of empirical relations describing the material (i.e.constitutive) or structural behaviour and obtained by the testing of structural models or full scale specimens under conditions that adequately simulate the structural conditions in terms of the range of values of the control variables, the type, magnitude and distribution of the applied loads, and the type of support conditions.
ii) the derivation of mathematical models of the system in question via a strong or weak formulation of the relevant physical laws and their solution.

Nevertheless, there has been some work done though of a preliminary nature. The extent of the work is such that the Proof of Concept stage of the investigation has been completed. Said work has been in three general areas: ferrocement overlays for improving the aseismic characteristics of brittle or deteriorated materials, the use of ferrocement for confinement, and ferrocement as an element in lateral resistive systems. The unanimous conclusion of these investigations is that the use of ferrocement increases the aseismic properties of the materials or systems to which they are applied to a very significant extent (Sun, 1984; Prawel and Reinhorn, 1985; Reinhorn and Prawel, 1985a, 1985b; Wang, 1985; Prawel et al., 1986; Yuzugullu, 1988; Balaguru, 1989).

Given the non-rigorous nature of the investigations the following are the areas of deficient research:

a) Ferrocement under in-plane shear (as explicitly stated in the State-of-the art Report on Ferrocement, ACI Committee 549, 1982).
b) Hysteretic behaviour of ferrocement structural members, subassemblages and systems.
c) Rigorous dynamic comparative study of aseismic structures containing pure ferrocement or ferrocement hybrid elements.
d) Rigorous study of the use of ferrocement for improving the hysteretic behaviour of conventional materials.
e) Rigorous study of the use of ferrocement for the suppression of brittle failure modes in low-ductility materials.

The authors envisage that ferrocement can be utilized in the aseismic design of structures in the following areas (Designs Patented):

a) Ferrocement-Masonry Hybrid Structural Walls for Box Systems.
b) Ferrocement-Masonry Infilled Frames.
c) Ferrocement Shear Panels
d) Ferrocement-RC Hybrid Shear Walls
e) Ferrocement-RC Hybrid Columns
f) Ferrocement-RC Hybrid Beams
g) Precast Ferrocement-RC Hybrid Beam-Column Joints.

In striking a balance between the region's aforementioned needs and project cost, the authors chose item (a) above. Specifically, the central idea is a rigorous study of local 100 mm clay walls with ferrocement overlays under cyclic lateral load. The study emphasises a retrofitting perspective viz. relative to conditions peculiar to existing walls such as plastering.

Objectives

The main objectives of this project are:

1. The development of a rigorously tested system for the upgrading and strengthening of existing clay brick structures in the Caribbean using ferrocement.

2. The formulation and dissemination of a set of simplified guidelines and rules for the dynamic, earthquake analysis and design of low-rise structures incorporating the system derived as per objective 1.
3. The promotion of ferrocement as a versatile construction material with characteristics optimally suited to developing regions, and especially the rural areas.

The benefits to be derived from this project are:

1. Significantly reduce the likelihood of building collapse and hence loss of life in the event of a major earthquake especially in rural areas.
2. Save foreign exchange by reducing the demand for steel via the use of ferrocement.
3. Create jobs in the construction sector since ferrocement construction is labour-intensive.
4. Promote the self-help concept since ferrocement construction requires a minimum of technical supervision.
5. Contribute to a database of the engineering properties of Caribbean materials.
6. Promote cooperation between the region's technical, developmental and financial institutions.

Scope of Work

The intended scope of work will be in the areas of Engineering Experiments, Structural Analysis and Design Formulations, Software Development, and Information Dissemination as follows:

Experimental:

There are three types of possible cyclic lateral load test at this time: the shaking table test, the pseudo-dynamic test, and the pseudo-static test. The shaking table test is closest to the ideal in that the actual ground acceleration measured in a previous earthquake is simulated. In the pseudo-dynamic test, though dynamic conditions are simulated, the method is that a computer, linked to the testing machine, solves the equations of motion for the system under the idealized earthquake and applies the calculated inertia forces at the floor levels. Both these test methods require sophisticated equipment. The pseudo-static test is not a dynamic test in that the rate of application of the load is so low that inertia forces are not applied. Cycles of reversed load are applied to the structure in increasing displacement amplitudes until failure. However, this test method adequately captures the most important dynamic material characteristics of the structure: the behaviour of the hysteresis loops (i.e. whether strength degrading; pinching; slipping, etc); the most distressed zones; the ductility capacity, and the strength. The pseudo-static method does not give the time history response of the structure under a particular earthquake record as does the shaking table or pseudo-dynamic tests, but such data can be obtained with sufficient accuracy by using the hysteresis model derived from the pseudo-static test in a MDOF dynamic analysis of the structure with the earthquake record as the applied load. Due to its high performance-to-cost ratio the pseudo-static method is the most widely used test method for accessing a structure's performance under dynamic conditions especially as a first approach. The pseudo-static test method will be utilized in this study.

The research is being conducted at the Structural Engineering Laboratory at the St. Augustine Campus of The University of the West Indies. The Laboratory comprises of a perforated strong floor (12 m x 25m) with a test load capacity of 100 tons, and specially designed strong walls for dynamic testing of up to 50 tons.

The effects of the control variables on the seismic response of the walls will be presented with said response being the hysteresis loops; lateral displacement; displacement dutility; stress and strains at the measured zones where applicable, and out-of-plane displacement. It is intended that hysteretic models be derived based on the observed results in a manner parallel to the well known Takeda model (Takeda et al., 1970) used for reinforced concrete. These models will be developed by applying systems identification procedures to the recorded hysteresis loops. Based on the observations, formulae that determine the ultimate shear resistance of the walls will also be presented.

Analysis and Design:

The analyses to be performed will consist of MDOF dynamic analyses of low-rise buildings using the derived hysteresis models, as well as finite element analyses of the walls based on the responses from the dynamic analyses. Comparisons will also be made of results from the analyses of clay wall buildings without the ferrocement overlays, and those with the overlays.

Also to be developed are formulae for the strength and ultimate deformability of the ferrocement/clay block walls.

Software Development:

The development of a user-friendly (windows 3.x) PC Software Package incorporating the derived formulae and methods for maximum design productivity. The computing facilities at the Department of Civil Engineering consist of a client-server networked environment of DEC VAX mini-systems, Sun and DEC workstations, and AT-compatible micros.

Information Dissemination:

The production of construction manuals for do-it-yourself enthusiasts and professionals, and the holding of seminars.

Experimental Programme

The experimental programme is shown in Table 1. In order to derive the hysteresis models, the skeleton or primary curve must be known for each wall. Therefore 2 specimens of identical configuration must be prepared: one for testing monotonically and the other for the cyclic testing. Also, in order to determine the walls' damping ratio, forced vibration testing will be conducted on select specimens. Since this test is conducted in the elastic range, additional specimens will not be needed. Each wall specimen is approximately half scale and measures 2.44 m in length (8 ft.) and 1.83 m high (6 ft).

Control Variables:

The control variables for the experiments, their values, and the reasons for those specific values are as follows:

(a) Mesh type

It was decided to use two types of mesh: square welded mesh and hexagonal mesh. Heavier gauges of ferrocement mesh are more readily available for square-welded meshes than other types and given the continuous reinforcing, may be more suitable for strength enhancement. The hexagonal mesh is, however, the most common and since high consideration is being paid to the upgrading of existing structures, the effect of this type of work is important.

(b) Number of mesh layers

The number of mesh layers to be used are 3, 5 and 7. For the specific gauge and spacing of mesh that is intended, it is known by the authors' previous experience that 7 layers is a practical upper limit from the point of view of construction difficulty. Since some significant degree of strength enhancement would be needed, 3 is a good lower limit. Also, previous studies by Clarke and Sharma (1991) have indicated that it is possible that

TABLE 1. EXPERIMENTAL PROGRAMME

SPEC. NO.	N	L.T	M.T	A.T	A.M.T	REMARKS
1M	-	M	-	-	-	Control 1
1R	-	R	-	-	-	Control 2
2M	-	M	-	-	-	Control 1
2R	-	R	-	-	-	Control 2
3M	-	M	-	-	-	Control 1
3R	-	R	-	-	-	Control 2
ACL-M	-	M	-	-	1	Aseismic clay design
ACL-R	-	R	-	-	1	Ditto
ACO-M	-	M	-	-	2	Aseismic concrete design
ACO-R	-	R	-	-	2	Ditto
A3-MH	3	M	HEX	A	-	-
A3-RH	3	R	HEX	A	-	-
A3-MS	3	M	SW	A	-	-
A3-RS	3	R	SW	A	-	-
A5-MH	5	M	HEX	A	-	-
A5-RH	5	R	HEX	A	-	-
A5-MS	5	M	SW	A	-	-
A5-RS	5	R	SW	A	-	-
A7-MH	7	M	HEX	A	-	-
A7-RH	7	R	HEX	A	-	-
A7-MS	7	M	SW	A	-	-
A7-RS	7	R	SW	A	-	-
B7-MH	7	M	HEX	B	-	Alternative bonding method
B7-RH	7	R	HEX	B	-	-
B7-MS	7	M	SW	B	-	-
B7-RS	7	R	SW	B	-	-

LEGEND:-

N - No. of mesh layers
M.T - Mesh Type
A.M.T - Aseismic Masonry Type

L.T - Load Type
A.T - Anchorage Type
M - Monotonic load
R - Reversed load

coupling between in-plane and out-of-plane deformations would result for even numbered mesh the effect of which is not well known and hence should be suppressed.

(c) Mesh orientation angle

A mesh orientation angle of 0° from the edge of the wall will be used. This angle was chosen because of ease of construction. Other angles, as well as lamination variables (which depend on the layers' orientation angles) (Clarke and Sharma, 1991), were not chosen for investigation given the priority of the research needs, i.e., the greater importance of ease of construction rather than optimal designs.

(d) Masonry type

In addition to the local 100 mm horizontal core clay block, six inch concrete blocks will also be investigated for comparison as well as the recently available 100 mm vertical core clay blocks. Though blocks will be chosen from one particular manufacturer, comparisons will be possible via basic tests which will be conducted on blocks from other manufacturers.

(e) Anchorage technique

Prawel et al. (1986) have indicated the significance of the anchorage mechanism of the ferrocement overlay to the wall. Therefore, the two most popular approaches in the literature will be investigated.

(f) Vertical pressure

The unique feature of local clay blocks is the horizontal orientation of the cores. This means that the bond strength at the wall's base becomes a critical issue due to the lack of vertical steel in the core which anchors the wall to the foundation. It is reasonable to believe that a possible mode of failure is in sliding. The lack of vertical steel may also have an effect on a flexural failure mode due to lifting of the corners. The vertical pressure due to roof load may have a significant effect on the bond strength which would resist both this sliding and lifting. In addition, the greater the roof load, the greater the earthquake's inertial force applied to the wall. However, due to a pre-stressing action, the greater the roof load, the stronger the wall also. We therefore have a vicious circle effect making it impossible to make generalized statements about the effect.

The sensitivity of the wall's performance to the vertical pressure will be investigated by applying reasonable extremes of roof load for a number of select specimens.

(g) Cross wall tie-in

The tie-in of the wall to the cross wall may affect the wall's performance by affecting its tendency to slide or lift. Tie-ins will be provided for a few select specimens in order to determine this effect.

Reference Specimens:

In addition to making comparisons on the effect of the aforementioned control variables on the seismic performance, comparisons will also be made with conventional systems which will serve as reference specimens. Masonry walls, each of clay block and concrete, and reinforced for gravity load only will be tested. These walls will also be used for checking the data acquisition and loading apparatus at the start of the tests. Concrete and clay block walls designed for seismic resistance will also be tested such that there is an equal percentage of steel reinforcement and mesh hence facilitating comparisons between the technical efficiency of both systems.

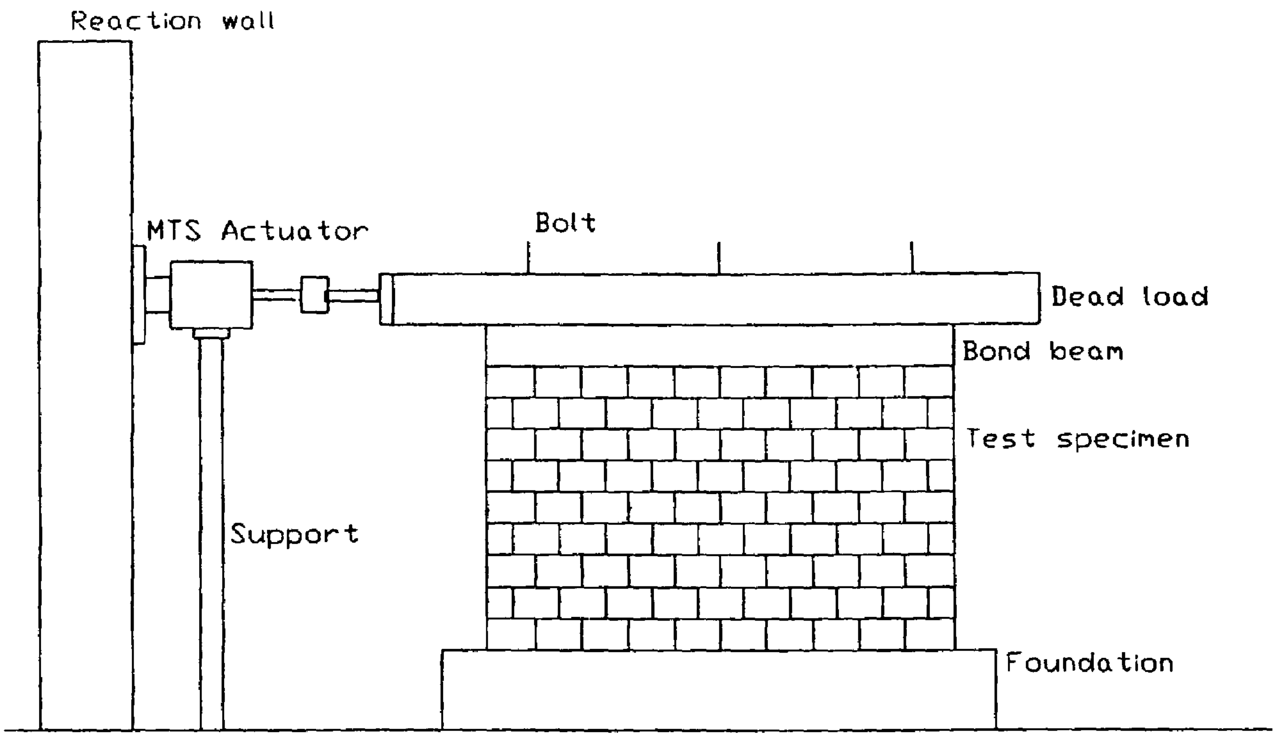

Figure 3: Experimental Test Set-Up

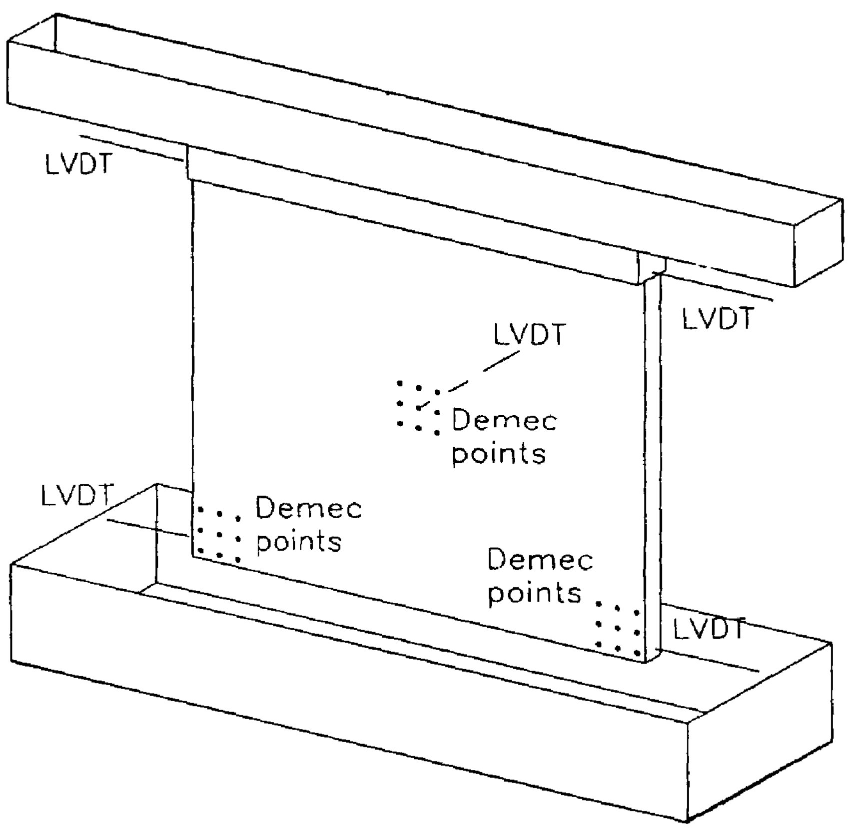

Figure 4: Test Set-Up Instrumentation

Instrumentation

The test set-up is shown in Figure 3. The load will be applied at the end of a slab simulating the effect of the roof, and which is bolted to the bond beam of the wall. The load will be applied via hydraulic actuator attached to the reaction wall, through a load cell and under a prescribed displacement pattern directed by a MTS structural testing machine.

Physical data will be acquired from strain gauges for steel only for those specimens with vertical cores. Demec gauges will be placed at the corners and centre of the wall on both faces. In-plane displacement will also be measured at the top of the wall using a LVDT, and out-of-plane displacement (for checking buckling) will be measured at the wall's centre also by LVDT. An x-y plotter will be connected to give real-time load-displacement readings. These transducers will be connected to a computerized data acquisition system and the data stored on disk for subsequent analysis. The instrumentation is shown in Figure 4.

Conclusions

This research project is at its early stages of implementation. As such the experimental programme is subject to change especially when the effect of vertical pressure is studied. For this reason it is those specimens relevant to the study of this factor which will be first tested. Provision has already been made in the event that it is proven that wall sliding is an imminent feature of the wall's behaviour. If this is the case, the anchoring of the wall to the foundation would have to be included as part of the retrofitting method.

The project is intended to cater for the needs of the region as a whole and therefore the upgrading cost implied by this study may be a considerable amount. In the interest of the optimum use of resources, additional verification of the findings most relevant to the upgrading cost may be sought via more elaborate testing at an earthquake engineering lab (e.g. shaking table testing of full scale models).

The project officially began on August 4, 1993. There is no significant conclusive data to report at the time of writing. It is envisaged that the project's duration will be approximately 2 years.

Acknowledgements

The authors wish to thank the European Community for providing the project's funding via LOME III thereby making this project possible, the St. Augustine Campus Grants Fund of The University of the West Indies for providing a portion of the funding for the materials, and Trinidad Aggregate Products Co. Ltd. of Trinidad and Tobago, for their donations of blocks and tradesmen services.

References

ACI Committee 549 (1982). State-of-the-art Report on Ferrocement. Concrete International, 4: 13-38.

Al Sulaimani, G.J. and Ahmad, S.F. (1988). Deflection and flexural rigidity of ferrocement I- and Box Beams. J. of Ferrocement, 18: 1-12

Balaguru, P.(1989). Use of Ferrocement for confinement of concrete. J. of Ferrocement, 19: 135-140.

Central Statistical Office (1974). 1970 Population Census. Bulletin No. 2, Port of Spain, Trinidad.

Clarke, R.P. and Sharma, A.K. (1991). The Experimental behaviour of Ferrocement flat plates under biaxial flexure. J. of Ferrocement, 21: 127-136.

CARICOM Secretariat (1985). Caribbean Uniform Building Code (CUBiC). CARICOM, Georgetown, Guyana.

Prawel, S.P. and Reinhorn, A.M. (1985). Seismic retrofit of structural masonry walls using a Ferrocement overlay. Proc. 3rd. North American Masonry Conf., pp. 1-59.

Prawel, S.P., Reinhorn, A.M. and Kunnath, S.K. (1986) Seismic Strengthening of structural masonry walls with external coatings. Proc. of the 3rd U.S. Natl. Conf. on Earthquake Eng., pp. 1323-1334.

Reinhorn, .A.M. and Prawel, S.P. (1985a). Ferrocement for Seismic Retrofit of Structures. Proc. of the 2nd. Intl. Symp. on Ferrocement, Bangkok, Thailand pp. 157-172.

Reinhorn, A.M. and Prawel, S.P. (1985b). Experimental study of Ferrocement as a seismic retrofit material for masonry walls. J. of Ferrocement, 15: 247-260.

Sun, N.C. (1984). Development of a prefabricated Ferrocement housing system. AIT, Bangkok, Thailand.

Takeda, T., Sozen, M.A. and Neilsen, N.N. (1970). Reinforced concrete response to simulated earthquakes. ASCE Journal of Structural Engineering, 96: 2557-2573.

Tomblin, J. (1978). Earthquake parameters for engineering design in the Caribbean. Proc. of the 1st Caribbean Conf. on Earthq. Eng., January 1978, Port of Spain, Trinidad.

Wang, M.L. (1985). The building system of Ferrocement light panel elements. Proc. of the 2nd. Intl. Symp. on Ferrocement, Bangkok, Thailand. pp. 457-468.

Yuzugullu, O. (1988). Ferrocement to increase the lateral resistance of timber-framed rural houses. J. of Ferrocement, 18: 35-39.