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THE INTEGRAL MASONRY SYSTEM WITH ADOBE TESTED IN LIMA FOR EARTHQUAKE RESISTANT CONSTRUCTION

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ABSTRACT

This paper presents an adaptation of the Integral Masonry System (IMS) developed in Europe under the trade name of the “AllWall System”, for concrete or clay, block or brick masonry walls using just mortar. In this case the system is modified to suit adobe block to allow the construction of housing in seismic areas.

The prefabricated truss-reinforcement employed in the IMS is made from electrowelded galvanized wire and comes in 5.85 m lengths arranged in the form of a 0.3 m truss. This truss-reinforcement may intersect in the three spatial directions and allows the construction of reinforced walls and slabs with these very lightweight and manageable components. These only require infilling with adobe to provide sufficient rigidity to the structure.

A two-storey 3 m x 3 m x 3 m adobe based integral masonry system has been tested on a seismic plate at one half scale at the PUCP (Pontificia Universidad Católica del Peru) in Lima in collaboration with the UPM (Universidad Politécnica de Madrid) in order to assure the viability of this new type of building construction for seismic areas in the Third World.

The results of this test (at 0.5 scale of a 6 m x 6 m x 6 m building) have shown that the Integral Masonry System remains stable without significant cracking, even with a 0.13 m displacement seismic movement equivalent to a magnitude of 10 on the Richter scale.

KEYWORDS: Integral Masonry System, earthquake resistant construction, adobe, truss-reinforcement.

INTRODUCTION

At the International Conference SismoAdobe 2005, held in Lima, a system of self-buildable adobe dwellings was proposed for earthquake areas, employing a new type of pre-welded truss-reinforcement which would be assembled on site [1]. At the ISES-2007 in Bangalore, a variation of this model was proposed for use in mud dwellings [2].

The Pisco earthquake (Peru) occurring in August 2007 led to the destruction of adobe dwellings and the loss of hundred of lives. It was subsequently decided to experiment with the reinforced masonry proposal with a view to introducing this alternative construction system to allow the construction of safe housing resistant to natural catastrophes.

The design of the standard housing is based on the dimensions of standard prefabricated truss-reinforcement which comes in 5.85 m lengths to allow ease of transport in the back of a small lorry (6.0 m) or on the roof rack of a car, given its light weight (approx. 8 kg/piece).

One or two-storey houses are considered, taking full advantage of the nigh on 6m lengths of truss-reinforcement and employing 0.3 m thick walls. The structural modulation may be 0.3 m and the spatial modulation 0.90 m, in order to give the following prototypes:

Table 1: IMS Standard houses

Bungalows				
Type 1	5.10 x 6.00 m	30.6 m^2 total area	24.3 m^2 floor area	1 bed
Type 2	6.00 x 6.00 m	36.0 m^2 total area	29.2 m^2 floor area	1 bed
Type 3	2 (5.10 x 6.00 m)	61.2 m^2 total area	51.3 m^2 floor area	2 beds
Two-storey houses:				
Type 4	2(5.10 x 6.00 m)	61.2 m^2 total area	51.3 m^2 floor area	2 beds
Type 5	2(6.00 x 6.00 m)	72.0 m^2 total area	58.4 m^2 floor area	3 beds
Type 6	2[2(5.10 x 6.00 m)]	122.4 m^2 total area	102.6 m^2 floor area	4 beds

OBJECTIVES

The research on this project was made with the following objectives:

- *At an experimental level*: to provide laboratory validation of the new building technique under seismic movement.

- *At a technical level:* to develop a construction system moderately vulnerable to the impact caused by natural disasters, based on prefabricated components, rapid construction and minimum cost.

- *At a social level*: offer developing societies a technological model of housing with models adapted to their lifestyle and based on self-construction.

House type 5 has been selected from the six proposed types of dwelling. This being a 6 metre long cubic shape and allowing the testing of the entire dwelling, even when built at half scale (Figure 1), and one which perfectly adapts to the possibilities of the seismic test table (4 m square). The prototype was constructed and tested at the anti-seismic structure laboratory at the Engineering Department of the Pontificia Universidad Católica del Peru (Lima), the leading department of its type in the country.

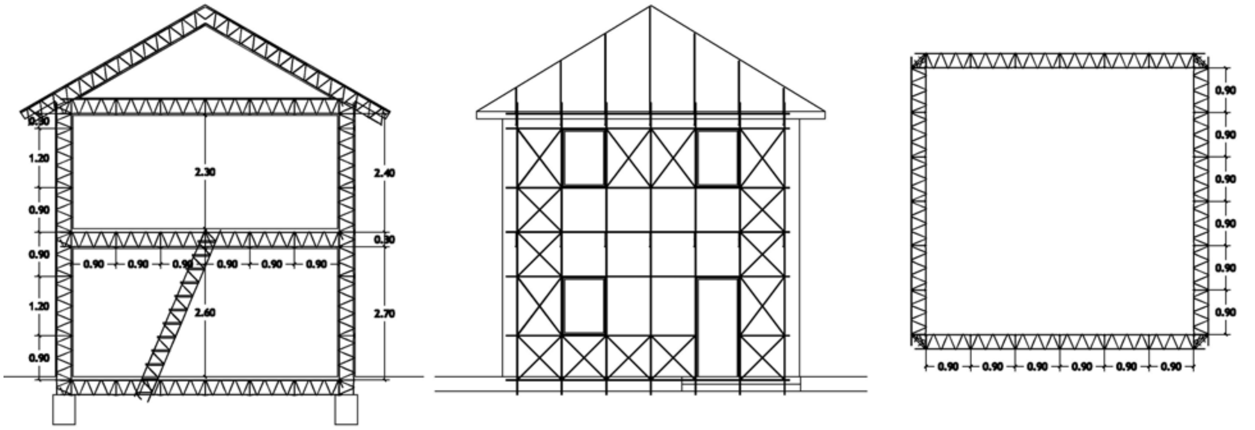

Figure 1: Type 5 house:
a) Section with truss-reinforcement set in walls, slabs, roof and stairs;
b) Elevation showing truss-reinforcement prior to rendering;
c) Plan showing wall truss-reinforcement.

CHARACTERISTICS OF THE MATERIALS EMPLOYED

The materials employed in the construction of the test prototype are: rolled steel (perimeter ring), galvanized steel (truss-reinforcement) with a strength of 50 kN/cm^2 in walls and slabs, and adobe in the perimeter walls with a compressive strength of 0.03 to 0.05 kN/cm^2. The truss-reinforcement were shipped from Madrid to Lima.

The rectangular adobe blocks are 0.28 x 0.15 x 0.08 m and composed of a 5:1:1 earth sand and straw mix, though given the spacing of the trusses in the wall and in their intersections at the corners, a very large number of square adobe blocks were also employed. These blocks were prepared in two piece moulds (Figs. 2a and 2b).

The prefabricated galvanized wire truss-reinforcement is arranged with a manual interlaced, taking into account the different width of 0.1 m between the truss-reinforcement in the following layouts:

One truss-reinforcement of test model (3x3x3 m): Two 0.05 m longitudinal wires each side of a 0.05 m zigzag truss wire, with 0.15 m spacing between longitudinal truss-reinforcement and 0.15 m between transversal truss-reinforcement (0.15 m wide).

The other truss-reinforcement of test model (3x3x3 m): Two 0.05 m longitudinal wires each side of a 0.05 m zigzag truss wire, with 0.15 m spacing between longitudinal truss-reinforcement and in this case, 0.14 m between transversal truss-reinforcement (0.14 m wide).

The adobe block wall was made 0.15 m thick. The truss-reinforcement in the walls and slabs has been arranged in 0.45 m interlaced modules in both the vertical and horizontal direction.

THE IMS CONSTRUCTION SYSTEM

The truss-reinforcement system consists of interlaced truss-reinforcement which crosses over each other in a three-dimensional manner. The voids are subsequently filled with brick, block, adobe, mud or recycled material in order to form the walls and boarding may be set on the trusses to form the floors.

The IMS adobe prototype only employs mud as infill and as this cannot possibly transfer the bond stresses of the truss-reinforcement, it is necessary to employ pre-welded or duly inter-connected truss-reinforcement, by means of threading or bolting them together, which will then transfer the stresses within the same. It is recommended that a final waterproof finishing of mortar reinforced mud or render be employed, even though the reinforcement is already protected against corrosion by its galvanized coating.

The first stage of the construction of the test prototype began in July and consisted of the preparation of the adobe blocks to allow these to dry out prior to the raising of the walls.

Figure 2: Preparation of adobe blocks:
a) Mixing; b) Adobe blocks drying in a covered yard.

The second stage consisted of the preparation of a supporting ring for the prototype, using HEB 200 profile and including the fixing plates to the test table and handles for the raising and transfer of the ring to the table. A coat of rustproof paint was applied after the welding work (Figure 3 a).

The trusses were then threaded and the intersections were fixed by wire (Figure 3b) and the trusses welded to the ring. Three slabs were also assembled: a base slab set on the perimeter ring; an intermediate floor slab; and an upper slab acting as a flat roof and on which sacks of sand were placed during testing to simulate the weight of the roof.

In the ensuing third stage, the 0.15 m thick walls were raised in courses of rectangular and square adobe blocks (Figure 4a). Raffia strips were set in the joints (Figure 4b) to be tied to a reinforcement mesh for the rendering. In order to aid the bond to the steel ring, the first course of blockwork was fixed with cement mortar. The openings (a door and three windows) were only made in the faces perpendicular to the movement of the test table.

Figure 3: a) Construction of 3 m x 3 m outer ring; b) Wire connection between trusses

A polyethylene geomesh with 0.15 m openings was tied to the wall by the raffia strips on just two sides of the prototype. This was made with the aim of verifying the differences between the rendered and unrendered faces after testing on the displacement table.

Figure 4: a) Dry test; b) Courses of adobe blockwork in the outer wall of the prototype.

At the end of October, one month after completing the construction of the prototype and once the wall joints had dried, the prototype was set on the test table (Figs. 5a, 5b and 5c).

Figure 5: View of the prototype prior to earthquake resistant testing:
a) On the test table; b) Upper view; c) Door.

The selected test sizing was as follows:

Reinforcement of test model (3x3x3m): Two 0.05 m longitudinal wires each side of a 0.05 m zigzag truss-reinforcement wire, with 0.15 m spacing. 0.15 m thick adobe block wall. The truss-reinforcement in the walls and slabs has been arranged in 0.45 m modules in both vertical and horizontal directions.

This corresponds, at real scale (6x6x6 m), to a reinforcement of: Two 0.01 m longitudinal wires each side of two 0.05 m zigzag truss wires, with 0.3 m spacing. 0.3 m thick adobe block wall. The 0.45 m truss-reinforcement modules employed in the walls and slabs in the test model correspond to the 0.9 m spacing employed in the full-scale model. This structural organization allows the positioning of doors, windows and stairwells within the wall and floor structure.

The area of the longitudinal truss-reinforcement in the test has, subsequently, been scaled down to a quarter of that employed in the real truss-reinforcement, while the area of the zigzag trusses has been scaled down to just half.

Earlier calculations of seismic resistance had already given very optimistic results for the application of this new system and it only remained to directly test the prototype of an entire house, as the steel components had already been individually tested in Europe.

The flooring was not completely set in the prototype and this was purely formed by the reinforcement mesh, infill and finishings and additional loadings were simulated by the placement of sacks of sand.

Two of the walls were rendered (a front wall and side wall to the seismic action) with a polymeric mesh both inside and outside the wall, connected by raffia strips running through the wall and tied to the mesh.

The construction process is made very simple by the lightweight components, both in terms of the trusses (each 5.85 m truss weighing around 3 kg) and the adobe blocks, and the entire building could be rapidly assembled by just two people as a result of the prefabricated reinforcement (requiring 13 days for the assembly of the steel structure and 9 days for the laying of the adobe blocks).

TEST PLAN

The test was conducted on the shake table at the Anti-earthquake Structures Laboratory at the Pontificia Universidad Católica del Peru, the foremost authority in the country. The shake table only has one degree of freedom, that of displacement in one direction, as opposed to the six characterising a real earthquake. The research project - reference AL08-P(i+D)-01 – was funded by the Universidad Politécnica de Madrid, as part of the 2008 support programme for R+D projects and activities in Latin America.

The prototype was arranged in such a way that the facing walls with openings (door and windows) were set perpendicular to the direction of movement and the blank walls set parallel to the same.

The test table only has one degree of freedom as opposed to the six characterising a real earthquake.

The movement (command signal) applied to the simulator platform represented the longitudinal component (N8ºO) of the acceleration recorded in Lima during the Ancash Earthquake on 31 May 1970. The original recording, recorded by analogical accelograph, was processed by the United States Geological Survey (USGS) to obtain a corrected digital acceleration which served as the basis for the generation of the command signal, referred to as "mayo70" (the standard reference employed at the laboratory). As the testing was conducted at scale, a time-compressed version of this signal was employed ("mayo70co") modifying the main frequencies in accordance with that of the scaled structure. In this way, the 100 points per second of the original signal was altered to 133.3 points per second in the modified signal, in accordance with the scale factor (1/2) of the prototype. As a result of this operation, the compressed signal ("mayo70co") produced greater accelerations than the original signal for a specific displacement.

The dynamic test was conducted in a sequence of movements (phases) of increasing amplitude, under the same command signal. Each phase is defined by the absolute maximum displacement obtained. Three phases were initially programmed and where each phase was associated, in increasing order of intensity, of what could be considered to be a frequent earthquake (light), an occasional earthquake (moderate) and a rare (great) earthquake. In the case of the "mayo70co" command signal, these movements corresponded to maximum displacements of 20, 50 and 80 mm respectively. The expected accelerations at the base of the module for these displacements were approximately 0.3g, 0.7g and 1.1g.

A fourth phase was programmed at the outset, in the case that the module remained in good condition after the three phases indicated above and where a great earthquake would be repeated (maximum displacement of 80 mm). However, during the first three phases, the behaviour of the horizontal intermediate mesh, corresponding to a floor slab, was not seen to be as expected and this meant that the walls would be working at a height of 3m, identical to the model at full scale and it was subsequently decided to subject the model to the original command signal "mayo70" with a maximum amplitude of 130 mm (the maximum capacity of the shake table and equivalent to a magnitude 10.00 earthquake on the Richter scale) with an estimated acceleration at the base of 1.8g.

Measuring instruments were placed on the walls and where A0-A8 refer to accelerometers and D0-D10 measure the relative displacements.

Stage 1: 20 mm displacement, minor earthquake, no sizeable cracking observed.
Stage 2: 50 mm displacement, moderate earthquake, the prototype cracked
Stage 3: 80 mm displacement, great earthquake, the prototype cracked but continued to resist. In view of the good behaviour of the construction it was decided to apply the maximum seismic capacity of the table.
Stage 4: 130 mm displacement, epic earthquake, clearly visible cracking though without losing stability, as may be seen in Figs. 6 and 7.

Figure 6: Photographs of cracking after the 4th test (130 mm):
a) Rendered sides; b) unrendered sides

Figure 7: Photographs of damage before 4th test (130 mm):
Left: a) Indoors; b) Entrance. Centre: c) Unrendered sides.
Right: d) spalling of render; e) Prefabricated double truss-type reinforcement; f) Cracks in wall.

RESULTS AND ANALYSIS

The prototype was subject to considerable cracking under the largest displacement applied (130 mm) but remained stable. The cracks occurred along the lines of the reinforcement, though in the lower part they tended to be diagonal. The smallest cracks appeared in the uppermost part and the largest cracks closer to the base. The walls perpendicular to the seismic action, containing the window and door openings, incurred a smaller degree of cracking and in the blind, transversal walls, the adobe confined within the spaces between trusses collaborated in the seismic resistance of the building.

The behaviour of those walls with polymeric mesh and rendering was very similar to that of the purely adobe walls. The most damaged areas were found at the corners and where the wall was only made with square adobe blocks which were not bonded in with the rest of the wall.

The maximum values of the measuring instruments indicated the value and recording time during testing. At certain points the recorded accelerations may be seen to exceed the previously forecasted values and, in all cases, are above the stipulated seismic acceleration of 0.4g established in Peru.

The relative displacements D7 to D10 mark the maximum opening of the cracks measured during the test, and where the maximum value in phase 1 and 2 was 0.4 mm, in phase 3, 3.8 mm and in phase 4, 4.1 mm. The maximum displacements recorded at the top of the model were slightly higher than those applied at the base.

The truss-reinforcement confined between the adobe walls did not deform. However, the unconfined truss-reinforcement set around the openings were deformed as a result of the buckling of the compressed bars.

CONCLUSIONS

The test results show that IMS with adobe is earthquake resistant and was capable of withstanding the dynamic stresses imposed by the shake table without incurring any damage that might affect its stability. Even though the prototype was considerably cracked, with cracking of around 4 mm (phases 3 and 4), the service life of the building could be extended once these cracks had been repaired and the construction would then be capable of withstanding further earthquakes. This may then be seen as an ideal system for the construction of housing in seismic areas.

In order to validate the building system with a further degree of safety, it would be necessary to test a model at full scale. On account of the characteristics of the shake table it would also be necessary to test a model with a more critical architecture and one with the spans set in the walls parallel to the direction of movement.

The additional reinforcement provided by the polymeric mesh did not generally appear necessary, in spite of the lack of continuity of the wall imposed by the vertical truss-reinforcement. However, the corner areas of the building - the most damaged areas of the structure and where the adobe block was not confined by the trusses – would benefit from this mesh reinforcement. The trusses around the openings and not surrounded by adobe block were subject to buckling and, subsequently, require stronger fixing.

The building system was seen to be easy to erect and in spite of the fact that this was the first time the system had been used in the country, the builders quickly understood the process without any complication.

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