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A REPORT OF CONTEMPORARY RAMMED EARTH CONSTRUCTION AND RESEARCH IN NORTH AMERICA

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Abstract: Rammed Earth (RE) is enjoying a renewed interest in North America. Contemporary stabilized rammed earth (SRE) builds upon traditional RE and incorporates rigid insulation and reinforcing steel, enhancing the structural and energy performance of the walls while satisfying current building codes. RE structures are currently engineered by licensed Structural Engineers using the Concrete Building Code or the Masonry Building Code. The construction process of contemporary SRE utilizes modern equipment and portland cement as a stabilizer, which can create walls of very high strength and durability. These structural walls are suitable for a broad range of heating and cooling climates. The incorporation of rigid insulation, fully encapsulated in the core of a wall and protected from pests or degradation, creates a high mass interior wythe that is thermally separated from the exterior, resulting in high thermal performance. Modern formwork allows walls to be built without the use of through ties, common in concrete construction and in some RE construction. Appropriately designed formwork may be reused many times with little waste of materials. The North American Rammed Earth Builders Association (NAREBA) collaborated with Unisol Engineering Ltd. and the British Columbia Institute of Technology (BCIT) on a battery of tests to obtain preliminary data to be used in support of engineering design. The tests included compressive strength comparisons, pull out rebar testing of both horizontally and vertically placed steel, simple beam tests, and the deflection of two composite wall columns with an insulation core and two types of reinforcing steel connections between the RE wythes.

Keywords: Rammed earth, stabilized rammed earth, insulated rammed earth, contemporary rammed earth construction, structural walls, North American Rammed Earth Builders Association (NAREBA)

1 RAMMED EARTH OVERVIEW

Rammed earth is experiencing increased interest in residential, commercial, and institutional structures around the world. In North America this is being driven by the following: 1) A growing trend toward selecting building materials that are sustainable; 2) The growing adoption of green certification programs (such as LEED) which recognize the benefits of rammed earth; 3) An increased emphasis on selecting building materials that contribute to healthy indoor air quality; 4) The awareness that rammed earth has a longer life cycle than many other materials; 5) A desire to reduce the energy consumption associated with heating and cooling structures; and 6) The recognition that CO2 emissions associated with buildings are a major contributor to global climate change.

The rammed earth structures being built today in North America are based upon the traditional rammed earth methods yet possess significant and fundamental differences. These differences include: 1) A reduced clay component in the soil mix; 2) Stabilization of the rammed earth mix with portland cement; 3) The incorporation of interstitial insulation to improve thermal performance; 4) The addition of steel reinforcing; 5) The application of the masonry and concrete code principles by structural engineers in designing the structures; and 6) The mechanization of mixing, delivery, and ramming of the soil mix.

There is a simplicity and elegance to a traditional rammed earth wall. The materials embodied within it are truly raw before being transformed into a monolithic masonry wall. The embodied energy of such a wall is extremely low and, depending upon the equipment used, could be limited only to animal energy. Given a site with appropriate soils, a climate that is moderate and relatively dry, and a low risk of earthquake, this traditional wall could be expected to provide a comfortable structure for generations. Unfortunately much of humanity lives on sites that have significant risk from earthquake, or have weather that is neither moderate in temperature nor arid, and may not have ready access to the types of soil appropriate for traditional earth construction. Also, most structures built in North America must comply with local building codes; in these locations Stabilized Rammed Earth (SRE) provides a viable alternative.

There is no specific provision or mention of rammed earth in the building codes used in almost all of North America. While a few exceptions exist, most notably the US state of New Mexico (Chapter 7, Part 4 - The NM Earthen Building Materials Code) and Tucson/Pima County, Arizona (Appendix Chapter 71, Earthen Materials Structures), most local building departments have neither an understanding of rammed earth nor a local example from which to form an opinion or to create a construction and inspection protocol. This might present challenges when rammed earth is introduced to a new locale.

The closest analogies that currently exist in determining the appropriate structural requirements for a stabilized rammed earth (SRE) wall are the Concrete Building Code and the Masonry Building Code. Both standards are commonly referenced in the design and engineering of SRE walls. This approach has been supported by the most recent ASTM "Standard Guide for Design of Earthen Wall Building Systems". Currently, the application of the Concrete Building Code often results in 2500 psi (17 MPa) being specified as the minimum compressive strength for the SRE material. In the absence of available data on the strength of SRE walls, this minimum strength provides a level of assurance, as it is the minimum strength for concrete, and thus conforms to a standard readily accepted and understood. It is unclear if this strength is necessary or ideal, given the ecological costs associated with cement production, but given the lack of established engineering values for SRE, it might be unavoidable for the time being. Normally this requires the addition of Portland cement at a rate of 6-10% to the earthen mix (by weight) to achieve this.

Careful selection of the earthen materials for an SRE wall is required to consistently maintain the required minimum strength and each soil mix must be analyzed and tested to determine the appropriate amount of cement required to meet the minimum strength specified. There are other benefits beyond the ready acceptance of the structural integrity by engineers and building departments associated with such high strength SRE mixes; They are more durable and less prone to the effects of erosion from weathering and, when reinforced with steel, might prove more able to withstand the destructive forces of an earthquake. It is often necessary to use a blend of two or more soil components to achieve an appropriate mix design suitable for an SRE wall (Fig. 1).

Fig.1 One graded soil component of a two-component SRE mix design

The application of the concrete code for rammed earth walls has resulted in the steel reinforcing schedules that closely resemble that of a concrete wall. Vertical steel reinforcing is typically continuous from the footing to the wall top and horizontal steel is placed at intervals up the wall. The CRSI "Manual of Standard Practice" is typically followed in the location and placement of reinforcing steel. There are, however, significant differences in the construction of an SRE wall and a concrete wall. The placement of the rammed earth material and steel is a more lengthy and involved process in an SRE wall. One primary difference is that the horizontal steel must be placed periodically, during the earthen material placement, not prior to placement (as is typical in a concrete wall), to provide access for the wall builders during construction. Unimpeded access in the wall is necessary and the typical steel field inspection prior to concrete placement must be modified, as it is not possible to place the horizontal steel prior to placing the SRE material upon which it rests. It is not practical to have a building inspector on hand for each placement as it occurs. Vertical steel reinforcing spacing must be maintained during the material placement and ramming, which requires constant attention as the soil lifts are placed and compacted. In short, the construction of an SRE wall is more labor intensive and involves a much longer process than is typical of a concrete wall. Good soil compaction around the steel is important to ensure a good bonding of the material and mobility in the wall is one necessity to ensure this.

It is an interesting dilemma that SRE design and building professionals face: the higher strength walls are more durable and are engineered using established concrete and masonry models, yet in order to achieve the higher strengths the walls may drift further from the ideal of traditional rammed earth. It is a trade-off in that the structures have a larger initial carbon footprint due to the increased proportion of portland cement, yet the strength and durability are significantly improved. As one would expect, research shows that the primary source of embodied energy in an SRE wall is the energy used when making the cement. The energy used in the construction of a rammed earth wall is negligible when compared to the energy contained in the cement (Reddy & Kumar, 2010). However, the amount of energy embodied in an SRE wall compares favorably to a burnt-clay masonry wall. Not only are the SRE walls tested (at 8% cement content) significantly stronger than a burnt clay masonry wall (3.38 MPa vs. 2.89 MPa) but they achieve that strength with 15-25% of the embodied energy (Reddy & Kumar, 2010). It is worth noting that strengths of 17 MPa and greater are not uncommon with 8% cement content in the soils used by contemporary SRE wall builders in North America.

2 INTERSTITIAL INSULATION

Rammed earth has been used successfully in mild to hot climates as the thermal mass effectively moderates the daily temperature swings, creating a comfortable living environment. Yet RE has a low thermal resistance and tests have determined its R-value to be only 0.4 (CSIRO, 2000). It is the introduction of interstitial insulation that has allowed rammed earth to perform well in a broad range of climates where both the maximum and minimum daily temperatures are significantly above or below the desired indoor temperatures for weeks and months a time. Thermal conductivity tests demonstrate that an interstitial core allows the RE wall to achieve "high levels of thermal resistance" and can "actually improve the thermal mass performance over a solid RE construction" (Fix and Richman, 2009).

There are three types of insulation typically used in RE structures in North America. Extruded polystyrene (XPS) is commonly used in the US and Canada. It has a perm rating of 1.1/inch and an R-value of 5/inch. Its compressive strength is 25 psi. XPS is commonly available and is dense enough to withstand the compaction forces it is subjected to during wall construction without deformation (Fig.2). It is a closed cell foam that has a natural "skin", which makes the board resistant to moisture. It is designed specifically for use in masonry wall environments.

Mineral wool fiber insulations, made from basalt rock and slag, are used both in Canada and the US. They have an R-value of 4.3/inch and a density of 3.4 lbs. /cu. ft. These insulations are designed for use in a masonry wall cavity and have a perm rating of 27.2/inch. The insulation is prone to compression during the ramming process and may suffer some reduction in R-value as a result. Rockwool insulations have the added benefit of scoring points under the LEED system, an important consideration on LEED certified projects. These insulations can be more difficult to obtain in some regions. Comparatively, mineral wool insulations can be more difficult to work with because the mineral wool fibers can be a significant irritant to wall builders during wall construction.

Fig.2 XPS foam in SRE wall

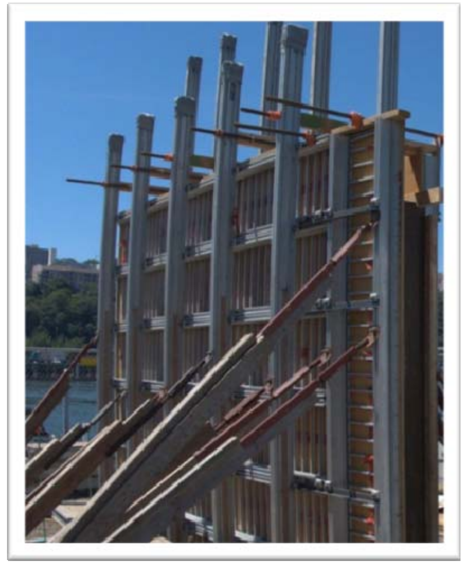


Fig.3 A NAREBA Formwork (fisheye lens)

Polyisocyanurate insulation (PIR), a member of the urethane family of chemicals, is a closed cell foam also used interstitially. It has the highest initial R-value of rigid insulations at 7.4/inch. That elevated R-value is partially the result of the blowing agent trapped in the foam during production. Over time this gasses off causing a deterioration of the R-value. This process may be slowed by the inclusion of a foil facing on the product but its long term R-value is rated at 6.5. It has a compressive strength of 25 psi and a perm rating of .03/inch. Careful selection of PIR insulation is required as not all types are appropriate for a masonry wall application. Further research on the constituent chemicals, production processes, and permeability is necessary to fully evaluate these insulations.

3 FORMWORK

The formwork currently used in the construction of RE walls varies widely. Wood framed and plywood faced formworks have been and continue to be used. They are frequently used on smaller projects or custom RE elements that require atypical form shapes. Commercial concrete forms have been modified to provide aluminum based support systems for the forming plywood. But this approach may require the significant modification of the forms as they are designed to be used with a through tie system, which may not be utilized on many projects, especially projects using an interstitial insulation, as this impedes the placement of ties. These forms do, however, provide a reusable formwork system that can deliver excellent results. Proprietary forms have been developed in Canada specifically for rammed earth builders but they have proven to be unnecessarily complicated and exceptionally expensive to both develop and produce.

The forces created during the repeated compaction of lifts of earth inside a form are extreme. A forming system must be capable of withstanding this in order to create walls that are plumb and straight. Additionally, the benefits of an efficient forming system are not to be underestimated. An example of NAREBA formwork is shown in Fig. 3.

4 CURRENT SRE RESEARCH IN NORTH AMERICA

Tests conducted at the British Colombia Institute of Technology (BCIT) in collaboration with Thor A. Tandy PE of Unisol Engineering and NAREBA, with funding provided by the Cement Association of Canada, reveal characteristics of steel-reinforced SRE walls that begin to shed light on the interaction of the RE material and the steel reinforcing configurations currently used by SRE wall builders. The test sample size is small and the results must be interpreted within that context. None the less, it is the first significant testing of a full-size insulated SRE column and the results are revealing about the nature of the materials. The tests included: 1) Compression testing of the soil mix; 2) Vertical rebar pull out tests; 3) Horizontal rebar pull out tests; 4) Flexural beam tests; and 5) Out of plane bending of vertical insulated columns with two different stirrup configurations. These tests were specifically designed to simulate the methods of construction typically used by NAREBA builders in the construction of insulated and uninsulated SRE projects.

4.1 Soil Mix Design

The soil mix was locally obtained and was composed of two components blended in equal amounts, then mixed in a drum mixer. The material was a 14mm (5/8") minus blend with a clay content under 7% by weight. The portland cement (Type II) content was 10% by weight. The water content was determined by performing a "ball test" in which the material will form a cohesive ball which shatters when dropped from waist height (roughly 7% moisture content). The material for all test samples was compacted using a pneumatic tamper with a 64mm (2.5") or 76mm (3") head.

4.2 Compressive Strength Testing

Compression strength testing was accomplished using cast cylinders (Fig.4) prepared by ramming the material into thirteen 150mm (6") diameter by 300mm (12") tall cylinders in PVC pipe in two successive six inch lifts.

Fig. 4 PVC cast cylinders

Fig. 5 Cylinders cored from test blocks

Twelve cylinders were created by coring into 480mm (19") wide X 600mm (24") long X 300mm (12") deep and 200mm (8") wide X 600 mm (24") long X 300mm (12") deep rectangular blocks that were formed in a manner representative of typical RE walls and insulated RE walls (Fig.5). The material in these samples was also rammed in two six inch lifts.

The compression tests were performed at a rate of 0.35-0.55 MPa/sec (50-80 psi/sec) on a 400 Kip Forney machine. The average strength of the rammed cylinder samples at six days was 12 MPa (1741 psi). This increased to 16 MPa (2221 psi) at 12 days. The samples cored from the blocks yielded strength of 15 MPa (2176 psi) at 16 days. The resulting 2% variation in strength is negligible and would seem to indicate that the ramming of RE test cylinders is an appropriate method for determining the compressive strength in the field.

4.3 Rebar Pull Out Tests

Rebar pull out testing was conducted on both vertically embedded bars (VPO) and horizontally embedded bars (HPO) in two phases of testing. Three diameters of deformed bar were tested: 10M (#3), 15M (#5), and 20M (#6). In Phase I two samples of each bar were oriented vertically. Additionally two samples of 10M bar were oriented horizontally (See Figs. 6-8). Phase II was conducted to compensate for anomalies present in Phase I.

In this phase, two samples of 15M and 20M rebar were rammed vertically.

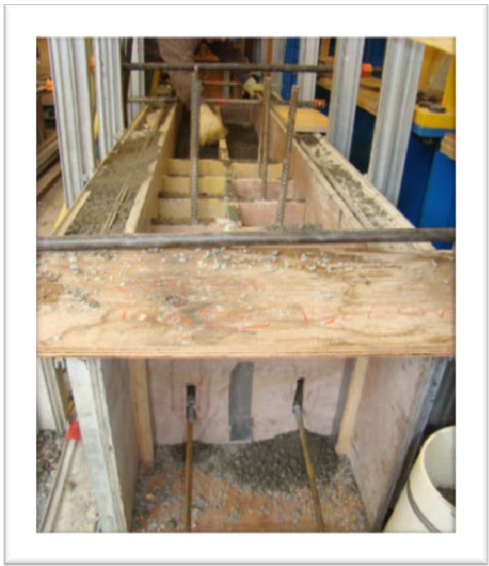


Fig. 6 Phase I- Vertical Pull Out (VPO) and Horizontal Pull Out (HPO) test samples during production

Fig. 7 Phase I –Horizontal Pull Out (HPO) test samples during production

Fig. 8 Phase I – Vertical Pull Out (VPO) test samples

A synopsis of the results from Phase I and Phase II provides the most accurate assessment of the bond strength. The VPO 15M samples in Phase I were damaged in handling and were unable to provide useful data. Phase II was designed to compensate for the lost data associated with these samples. The Phase II tests of the 15M (#5) VPO bars provided consistent results. The steel reached yield in both tests and the bond strength was 2.9 MPa (420 psi).

The 20M (#6) bars demonstrated the greatest bond strength values for the various rebars in both Phase I and II. They reached yield in Phase I with bond strengths over 5 MPa (725psi) and in Phase II pulled out of the sample after reaching bond strength of over 4 MPa (600psi).

The two 10M (#3) VPO bars tested with a high degree of variability. The first bar reached yield with bond strength in excess of 3 MPa and the second pulled out in excess of 1.5 MPa. The results of the two 10M HPO bars were consistent with a bond strength slightly less than 2.5 MPa (363psi). One sample reached yield and one pulled out. One 10M sample after testing is shown in Fig. 9 while a bar failure is shown in Fig. 10.

The results suggest that the ramming procedure has a direct effect on the bond stress. There might be a mechanical connection between the steel and RE that is unlike the cement bond that occurs in concrete or masonry models; this connection would likely be affected by the thoroughness of the compaction (Tandy, 2010).

Fig. 9 10M Sample after testing

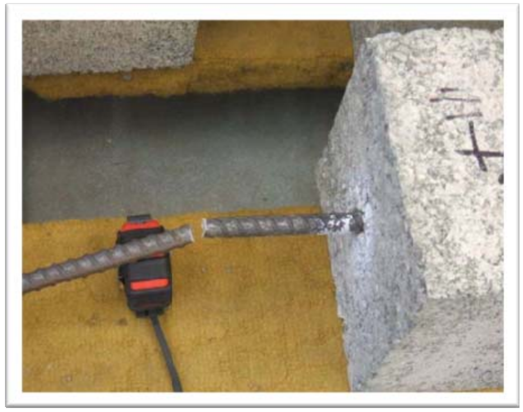


Fig. 10 Bar failure in Pull Out test

The test results outperformed the equivalent in concrete or masonry by a significant factor of up to approximately three and there was no significant difference of bond stress with the various bar diameters (Tandy, 2010). This would support the use of the concrete analogy in designing the steel reinforcing in future SRE projects, though it might result in overestimating the development length required.

Further testing is required to explore the ability of different SRE mixes, with lesser cement contents, to bond with the steel reinforcing. It is encouraging that yield was reached in many of the test samples but a larger sample size will be required in future tests.

4.4 Simple Beam Flexural Tests

Simple beam tests were conducted on two beams measuring 200mm (8") in width X 300mm (10") in depth X 1500mm (60") in length (Fig.11). One was constructed with two 10M deformed rebars and the other with two 15M deformed rebars. The beams were subjected to a 1 kN/minute load initially and 2 kN/minute load after 75 kN was reached, using a modified three point loading system (Fig. 12).

Fig. 11 Rebar placement in RE beams

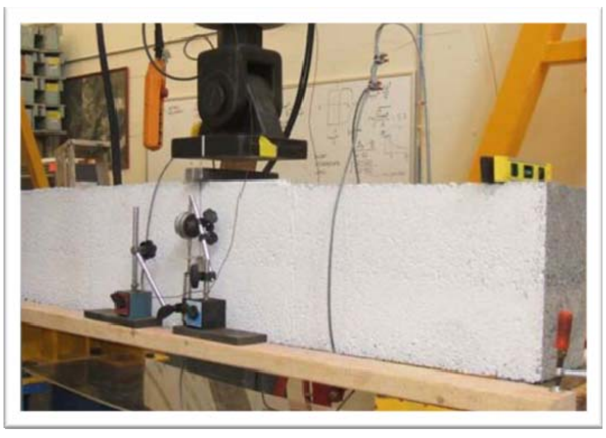


Fig. 12 Beam with 1420mm (4' 6") clear span.

Test Beam 1 was reinforced with two 15M (#5) bars. No initial flexural cracks were observed and the beam failed at a peak shear load of 78 kN. The deflection at the peak was approximately 5.5 mm (0.22”). The beam failed in shear (Fig.13).

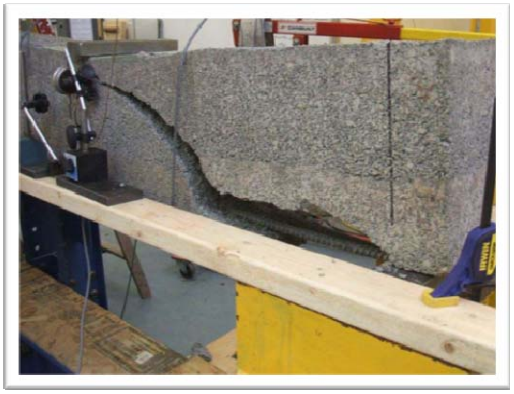


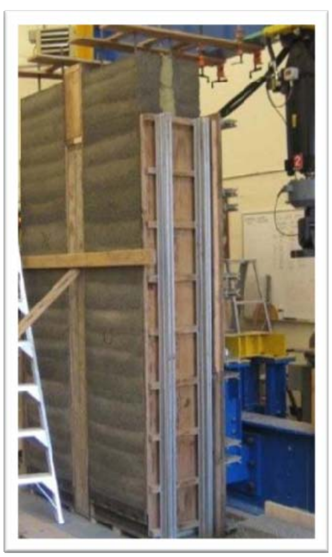
Fig.13 Test Beam 1 at failure

Fig. 14 Test Beam 2 at failure

Test Beam 2 was reinforced with two 10M (#3) rebars. The first crack was recorded at 38kN and the ultimate failure was abrupt at 60 kN with a deflection of approximately 4.5mm (0.17”). This beam also failed in shear (Fig.14). As no shear reinforcing was used in either beam test it would be interesting to incorporate it into future beam tests to determine what increased load capacity is created. The results from these tests may help establish a baseline for determining the elastic modulus for SRE in future design and engineering.

4.5 Composite Wall Column Out of Plane Bending

Two composite SRE walls columns (representative of a typical insulated SRE wall) were constructed using two different deformed 10M (#3) stirrup configurations, which are representative of steel configurations used by NAREBA builders in the field. The columns measured 600mm (24”) in width X 450mm (18”) in depth X 2650mm (106”) in height and each had two full height deformed 20M (#6) vertical rebars in each wythe (four per column) of SRE (Figs. 15&16). The wythes of SRE were separated by a 125mm (5”) core of mineral wool (Roxul 80) insulation that compressed approximately 13mm (0.5”) during material compaction.



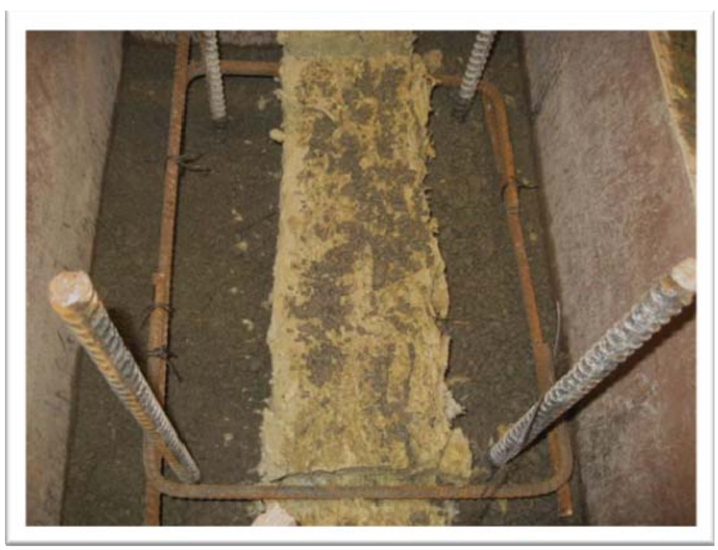


Fig. 15 Wall columns stripped of forms

Fig. 16 Steel configuration in Column I

The horizontal steel configuration of column I was a “U” shaped stirrup placed with a horizontal rebar every 600mm (24”) up the height of the wall (Fig.16). This configuration is simple to place and requires minimal cutting of the insulation.

The steel configuration in Column II was a more complex diagonal tie that hooked behind the vertical steel (Fig.17). The diagonal ties were placed with the horizontal steel every 600mm (24”) along the height of the wall. This steel is more difficult and time consuming to place and requires significantly more notching of the insulation.

Fig.17 Steel Configuration in column II (wood rebar spreaders removed during construction)

Fig. 18 Column under deflection (painted for improved crack visibility)

The columns were constructed on steel bases that permitted them to be hoisted onto an apparatus and supported horizontally at the base and cap (Fig.18). The load was applied along the entire face of the column via a steel channel attached to an actuator. Both columns were tested in displacement control. Dial gauges and two LVDTs were placed along the column width to record the mid-height deflection (Fig.19).

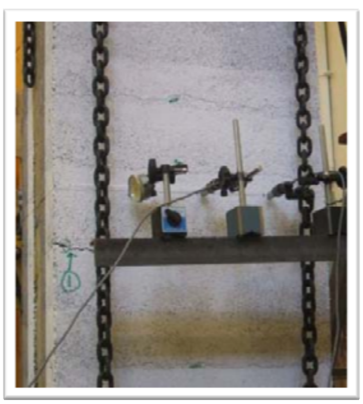


Fig. 19 Cracks visible and LVDTs

Fig. 20 Test Column after removal from lab

Column 1 was loaded to a maximum deflection of more than 30mm (1.2”) at a load of just under 60 kN. Cracks developed during this loading and were documented. Column 2, with the diagonal stirrups between wythes, recorded significantly higher loading. A deflection of 25mm (1.0”) was recorded at a load 155 kN. At this point the deflection increased with little additional loading. Various cracks occurred on the specimen during testing and were recorded. It is worth noting that neither sample suffered a catastrophic failure during the tests. They remained cohesive elements even when removed, via forklift, from the lab (Fig. 20).

The two insulated SRE columns met or exceeded the expectations of the researchers. It supports the use of either of these steel reinforcing approaches on single story walls. The diagonal stirrup in Column II resulted in a load capacity of approximately 250% that of the horizontal stirrup. This approach could be employed on taller walls or where shear loading is of greater concern.

5 FURTHER WORK

There are many areas of insulated SRE walls that warrant further research: 1) Further exploration of the cement bond and/or mechanical bond on deformed steel reinforcing; 2) The effects of shear reinforcing on beam tests; 3) The effects of rigid foam insulation on the shear capacities of composite SRE walls; 4) The bond strength of steel reinforcing in lower strength SRE walls that require less portland cement to construct; 5) A comprehensive analysis of the insulations used in composite walls; 6) The structural capacities of different wythes thicknesses in composite SRE walls; and 7) The strength capacities of SRE mixes that use an environmentally beneficial pozzolans component.

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