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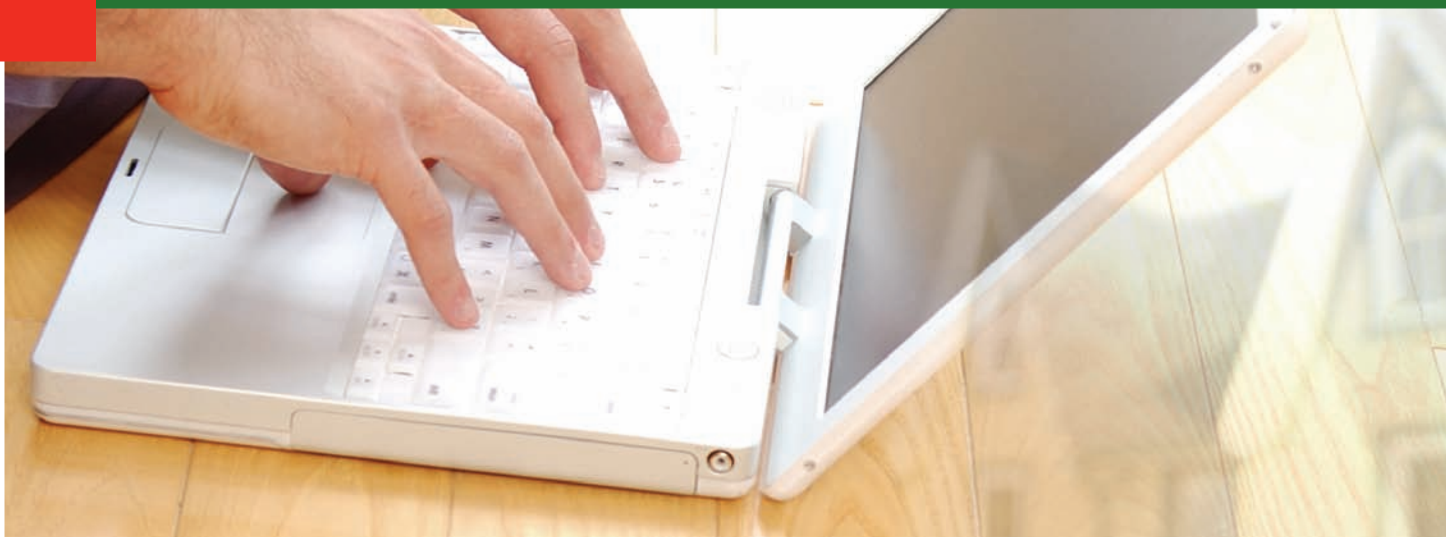

Effect of Mesh and Bale Orientation on the Strength of Straw Bale Walls

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EFFECT OF MESH AND BALE ORIENTATION ON THE STRENGTH OF STRAW BALE WALLS

FINAL REPORT
For the Canada Housing and Mortgage Corporation (CMHC)

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Co-Investigators: Chris Magwood, Steve Vardy

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Executive Summary

The objective of this research was to obtain data on the structural performance of straw bale construction to aid prospective home-owners, builders, building inspectors, and engineers. Structural testing of full-scale straw bale walls was being carried out in the Structures Lab of the Department of Civil Engineering at Queen's University, Kingston. Test walls were being constructed and subjected to compressive loading until failure. The stiffness and strength of each wall was measured, allowing a comparison to be made between various combinations of reinforcement, bale orientation, and plasters. In order to make this research as relevant as possible to the stakeholders, Chris Magwood, a builder and consultant on dozens of straw bale projects in Ontario, was actively involved in defining the most relevant parameter combinations and constructing the wall panels. The Ontario Straw Bale Building Coalition (OSBBC) and other sources around Canada have been consulted.

Sommaire

La présente recherche avait pour objectif d'obtenir des données sur la performance structurale des constructions à ballots de paille afin d'aider les acheteurs éventuels de maison, les constructeurs, les inspecteurs en bâtiment et les ingénieurs. Des essais structuraux de murs en grande réelle ont été menés dans les laboratoires de la faculté de génie civil de l'Université Queen's, à Kingston. Les murs ont d'abord ont été construits, puis soumis à des surcharges de compression jusqu'à la rupture. La rigidité et la résistance de chaque mur ont été mesurées, ce qui a permis d'établir des comparaisons entre les différentes combinaisons d'armature, d'orientation de ballot et de plâtre. De manière à rendre cette recherche la plus pertinente possible pour les intervenants, Chris Magwood, un constructeur et consultant sur des dizaines de projets en ballots de paille en Ontario, a participé activement à définir les paramètres des combinaisons les plus utiles et à la construction des panneaux de mur. L'Ontario Straw Bale Building Coalition (OSBBC) et autres sources de partout au Canada ont également été consultés.

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Introduction

This report describes a research project on the structural performance of straw bale construction undertaken for the Canada Housing and Mortgage Corporation (CMHC) at Queen's University in 2007. The number of straw bale houses in Canada is growing as homebuyers seek more environmentally friendly options. Straw bales offer excellent insulation, are a sustainable resource, and reduce the need for timber and the destruction of forests. Many home-owners concerned about the internal environment of a house and reducing the potential emissions created by conventional housing materials consider straw bale construction. It is also popular with Canadians seeking to build their own home, since the skills required can be readily taught.

A typical straw bale wall consists of stacked bales, wire or plastic meshing, and stucco skins. There are two main types of straw bale construction: (a) Load-bearing, in which gravity loads are carried by the plastered walls; and, (b) Post-and-beam, in which loads are carried by a timber frame, and straw bales are used as insulation only.

Straw-bale construction has experienced a revival in Canada since the mid-1990's and much of the test data in the literature reflects the practices in vogue at that time.
There is currently a lack of codes and standards for straw bale construction. As a result, it can be difficult for prospective straw bale home owners, builders, or engineers to convince building inspectors that this form of construction complies with Building Code specifications. In most cases a structural engineer must review the design. The engineer may require full-scale structural tests if a design is proposed for which test data is not available. This adds additional costs and puts straw bale construction at a disadvantge compared with other forms of residential construction.

Builders have improved or adapted basic straw bale construction in numerous ways since the first homes were constructed in Canada. A review of projects listed on the web-site of the Ontario Straw Bale Building Coalition (OSBBC 2008) lists 57 projects in Ontario alone. Of these projects, 42% involve load bearing straw bale walls. Among the variations in design that can be noted include: (1) bales oriented on-edge (33% of the load-bearing structures); (2) no mesh to reinforce the walls (21% of the load-bearing structures), or the use of Tenax (plastic) mesh for reinforcement; (3) use of earthen plasters, often mixed with fibres such as cat-tail fluff or hemp (25% of the load-bearing structures); (4) the use of hemp, rather than wheat straw, bales.

The focus of this proposal is the structural performance of load-bearing straw bale walls. The objective of this research was to provide structural performance data and information for prospective straw bale home-owners, straw bale home builders, building inspectors, and engineers. Structural testing of ten full-scale straw bale walls was undertaken. The test walls were instrumented and subjected to compressive loading. The stiffness and strength of each wall was measured, allowing a comparison to be made between various combinations of reinforcement, bale orientation, and plasters. In order to make this research as relevant as possible to the stakeholders, Chris Magwood, a builder and consultant on dozens of straw bale projects, was actively involved in defining the most relevant parameter combinations and constructing the wall panels.

The research question investigated by this research will be effect on the compressive strength of straw bale walls of three parameters: (1) orientation of the bales, either flat or on-edge; (2) methods of improving straw-plaster bond, including "clay slip" and Tenax mesh; (3) type of plaster, either cement or clay.

The report begins with a review of the current literature concerning the structural performance of straw bale construction. It then describes the ten walls constructed for this study, including the materials used, and construction techniques. The testing of the walls, including the instrumentation used, is described. The results are presented, followed by a discussion and conclusions. The original research proposal for CMHC indicated that walls with "wire mesh" reinforcement and walls with hemp bales would be tested. However, discussions with Chris Magwood indicated that Tenax, rather than wire mesh, is used in Canada. Therefore, Tenax has been substituted for wire mesh in the tests described herein. Chris Magwood also indicated that although the number of projects using hemp bales is increasing, the majority use wheat bales. To reduce the number of parameters to be tested and to focus on those of most concern to the straw bale community, all the walls described herein were constructed with wheat bales.

Included with this report is a DVD that contains video clips of the construction process and spreadsheets of all the data obtained during this research project.

Literature Review

Numerous experiments have been conducted in recent years on plasters, un-plastered straw bales, plastered straw bales, un-plastered straw bale walls and plastered straw bale walls. Unfortunately, due to a current lack of standardization for straw bale testing methods, and the inherent variability of straw bale construction, the results reported in the literature vary significantly from experiment to experiment. Despite this, the results do indicate that with the appropriate design considerations, a plastered straw bale wall can be constructed to meet a wide range of structural requirements.

Plaster structural performance

Most straw bale structures are plastered with cement/lime plaster sometimes referred to as stucco. More recently, earthen plasters have been gaining popularity amongst environmentally conscious builders. Earthbased plasters are made with soils that have a naturally occurring balance of sand and clay (Magwood et al., 2005). They have significantly lower values of embodied energy as compared to those of lime/cement plasters. Generally, earthen plasters have much lower strengths and moduli of elasticity than lime/cement plasters.

Lerner and Donahue (2003), Ash and Aschheim (2003), Grandsaert (1999), Nichols and Rapp (2001), and Faine and Zhang (2002), and Taylor et al. (2006) all tested various earth and cement plasters and found compressive strengths ranging from 0.23 MPa to 27.6 MPa, with earth plasters having strengths at the lower end of this range. Lerner and Donahue (2003) also found cement-based plasters had modulus of rupture values of approximately 1.4 MPa, while Taylor et al. (2006) found moduli of elasticity values for a variety of earthen and cement/lime plasters between 400 MPa to 2500 MPa.

Taylor et al. (2006) investigated the effects of moisture content, drying time, drying conditions, and clay content on the strength of earthen plasters. The earthen plasters were also compared to a plaster mixed using commercially available clay, and to cement-lime plasters. The results of this study show that earthen plasters can be used as a low strength structural material. The plaster was mixed using soil consisting of 69% silt, 27% clay and 4% sand. The cubes and cylinders of cured plaster were loaded until failure and showed similar strength values to those of low strength cement/lime plaster.

Increased clay content significantly increased the strength of the earthen plaster. For the earthen plasters, strength was found to increase linearly with clay content. Varying the moisture content at the time of testing by placing some specimens in a drying oven at 110° C and some in a moisture room with 100% relative humidity was intended to simulate plaster subjected to hot, dry weather or a heavy rainfall, with the laboratory air acting as the control environment. Placing the plaster in a 110 ºC oven substantially reduced the moisture content and increased the strength. Leaving the plaster in a humid environment increased the moisture content and resulted in lower strength as opposed to a lab environment.

Individual bale structural performance

Bou-Ali (1993), and Watts et al. (1995) performed experiments on individual straw bales to find the load deflection behaviour of un-plastered straw bales. Results suggest that the modulus of elasticity varies significantly from bale-to-bale, and that the density of the bales has a greater effect on the strength and stiffness of the bales than the type of bale.

Vardy and MacDougall (2006) conducted experiments on plastered straw bales and found compressive strengths ranging from 7.7 kN/m to 91.5 kN/m. In addition, the experiments conducted by Vardy and MacDougall (2006) studied the effects of the plaster thickness and strength on the overall strength of the plastered bale.

The bales used for experiments by Vardy and MacDougall (2006) had very consistent dimensions and plaster thicknesses which were achieved with the help of a wooden jig designed for this purpose. The jig was used to compress the bales to the desired dimensions and after the compression, as a guide to trim away the excess straw. A plastic frame was used around the edges of the bale to guide the plaster application and bring the plaster skins to consistent uniform thickness. This method reduces the variability of the experiments and ensures the clarity of conclusions.

Vardy and MacDougall (2006) tested plastered wheat bales oriented flat and on edge. The effects of the plaster thickness and strength on the overall strength of the plastered bale were examined. It was found that the strength of plastered bales orientated flat is 36% greater than those oriented on edge for a specific plaster thickness and strength. The plaster thickness was shown to have a greater effect on the plastered bale strength than the cube strength of the plaster. It was found that doubling the plaster thickness increased the average plastered bale strength by 65%, while doubling the plaster strength increased the average plastered bale strength by only 25%.

It is acknowledged that the uniform bale samples with consistent plaster thicknesses used for testing are quite different from actual construction. Even though in the real construction setting, the plaster and bale dimensions are highly variable, the results obtained in the study provide insight into the mechanics of straw bale construction and a solid base for further research. The conclusions can be used to guide design to obtain the optimum structural performance of the straw bale walls.

Bale wall structural performance

Bou-Ali (1993) conducted experiments on un-plastered bale walls subjected to out-of-plane bending, finding the walls withstood between 1 kPa to 5 kPa of pressure. Grandsaert (1999), Faine and Zhang (2002), Zhang (2002), Fibrehouse Ltd and Scanada Consultants Ltd. (1996) and Vardy and MacDougall (2007) all conducted experiments on the compressive strength of plastered straw bale walls, finding ultimate strengths of 20 kN/m to 90 kN/m for various tests conducted using a wide range of wall dimensions, plaster proportions and thicknesses, reinforcement schemes and bale types and sizes.

Vardy and MacDougall (2007) also noted the following key observations:

1. Assuming compression failure of the walls, the walls failed at 80% of the theoretical load based on the plaster strength and thickness.
2. Observations indicated buckling of the walls prior to failure with mid-height lateral deflections measured to be approximately 1.6 mm at failure.
3. A non-linear stress-strain concrete model was used to predict an approximate stress-strain response for the walls.

It is important to note that the experiments conducted by Vardy and MacDougall (2007) were on 6 walls built using jigs which provided very consistent bale and plaster dimensions. Again, it is acknowledged that although in a construction setting the plaster application and bale dimensions have significant variability, the results and observations provide a means for understanding the structural behaviour and failure mechanisms associated with plastered straw bale construction.

In 2001, a number of significant in-plane cyclic experiments were conducted in a test program funded by the California Department of Food and Agriculture and furthered the understanding of the seismic behaviour of plastered straw bale walls (King, 2006). Because of the small aspect ratio associated with plastered straw bale walls, they have shown an inherent stability ideal for resisting both minor and major earthquakes. It was shown that with adequate detailing, a straw bale wall containing steel mesh reinforcement with a lime/cement plaster performs on-par with conventional plywood-sheathed stud walls, and can be considered to have a ductility R-factor of 5.5 as per the 1997 Uniform Building Code seismic design formula. An earthen rendered straw bale wall with plastic mesh has low ductility, but it was shown to have similar lateral-load resistance to that of a very lightly sheathed stud wall. It was also noted that even after significant lateral deformations, the walls still managed to sustain significant compressive loads, indicating an ability to avoid collapse even when subjected to the lateral loading indicative of a major earthquake.

Materials

Two-string bales of wheat were used for all the walls constructed and were obtained from farms located approximately 50 km northwest of Kingston. The bales were harvested during the summer months of 2006 and subsequently stored in a barn.

Two batches of bales were used to construct the walls. The first batch was used to construct Walls 1 – 5 and the second batch was used to construct Walls 6 – 10 (the walls will be described in detail in the following section of the report). Table 1 indicates the average mass of a sample of three of the bales from each batch. All the bales had dimensions of 375 ± 10 mm x 475 ± 10 mm x 875 ± 25 mm . Thus, the bales used for Walls 1 – 5 had an average bulk density of 84 kg/m^3 and the bales used for Walls 6 – 10 had an average bulk density of 123 kg / m^3.

Two plasters were used. The first, called a “cement” plaster in this report, was a mixture of St. Lawrence Type N Mason’s Cement, mason’s sand, and water. The second, termed a “clay” plaster in this report, was a mixture of commercially obtained clay, mason’s sand, straw, and water.

Because construction of several walls took place during the winter months, it was impossible to obtain clay from a construction site as is typically done for earth plasters used for straw bale construction. Therefore, it was decided to use a commercially available clay, Turface Professional Mound Clay. According to the manufacturer, it is a naturally occurring, heat treated clay containing up to 5% sand. An analysis of the clay was not performed as part of this study.

The proportions of binder, sand, water, and straw (if used) for each plaster were specified by Chris Magwood based on his experience and are tabulated in Table 2. Following typical practice in the field, a bag of clay or mason’s cement was poured into the mixer. The sand was added by placing a specified number of “shovelfuls” of sand into the mixer. Finally, the specified mass of water was added to the mixer. Each batch of plaster was mixed in a gas powered mortar mixer, as shown in Figure 1, until the plaster was judged visually to be well-mixed and consistent.

For each set of walls, a set of three 50 mm x 50 mm x 50 mm cubes of the plaster was obtained and tested in compression following ASTM C109 (1998) to measure the compressive strength of the plaster.

In Canadian straw bale buildings, two approaches are taken to improve the bond between straw and plaster. For buildings using cement plasters, a polypropylene mesh with the commercial name Tenax Cintoflex D is affixed to the bales before plaster is applied. The rectangular mesh has openings of 1 inch by 1.5 inches. As shown in Figure 2, the mesh is provided in rolls of width 10 feet and was cut to length for the walls to which it was affixed.

For buildings with clay plasters, the bales are typically coated with a clay slurry termed "clay slip" before the bales are stacked and plastered. The clay slip is a mixture of clay and enough water that the mixture can be freely poured, as shown in Figure 3(a). The slip was then worked by hand into the fibres of the bales as shown in Figure 3(b).

Wall Construction

Ten walls were constructed and tested. Table 3 outlines the configurations of the walls.

As indicated in Table 3, the walls were constructed in four groups. In each case, the construction of formwork, and stacking of bales took place on the first construction day. Plastering then took place over the remaining days of the construction periods indicated. The construction of the walls was supervised by an experienced straw bale builder. Plastering was completed by graduate students at Queen's University except for the walls constructed April 28. In this case, some of the plastering was completed by members of the Sir Sanford Fleming College Sustainable Building class.

Four walls had clay plaster, and five had cement plaster. One wall (Wall 3) had one clay plaster skin and one cement plaster skin. This configuration is being proposed by some straw bale builders to address concerns about exposure of clay plasters to humid exterior environments.

Walls 1, 2, 4, and 5 provide a direct comparison of the effect of bale orientation on compressive wall strength for both cement and clay plasters. The bales used for Walls 6 and 7 were dipped in a thin clay slurry before stacking and plastering. The slurry is termed "Clay Slip" and it is purported to improve the bond between the plaster and bales, however no testing has been undertaken to verify this. These walls can be compared to Walls 2 and 4 respectively to quantify the effect of Clay Slip on compressive wall strength.

After stacking the bales for Walls 8 and 10, Tenax mesh was affixed to the surface before plastering as described in the following section. This mesh is purported to provide a surface for the plaster to bond to. These walls can be compared to Walls 1 and 5 respectively to quantify the effect of Tenax mesh on compressive wall strength.
Finally, Wall 9 is a replicate of Wall 5 and is intended to quantify the repeatability of the construction methods and test set-up.

The construction of all the walls began with assembly of the formwork as shown in Figure 4. The formwork consists of a top plate, a bottom plate, and two side plates. The top and bottom plate was constructed using 2” x 4” (38 mm x 89 mm) studs and a single layer of ½” (12.5 mm) plywood. Figure 5 shows a cross-section through a typical top or bottom plate. The plates were constructed so that there is a 25 mm overhang of the plates on each side of the bales. This overhang is used as the guide for determining the required thickness of plaster. It also ensures that roof loads (in the case of a building) are transferred directly to the plaster skins. The 2” x 4” (38 mm x 89 mm) studs are connected to the plywood by decking screws every 600 mm.

Note that in Canada, a typical top plate in a straw bale building would consist of 2” x 6” (38 mm x 140 mm) studs sandwiched between two layers of ½” (12.5 mm) plywood. Therefore, the top plates used in all the testing reported herein were considerably more flexible and weaker than those used in typical straw bale construction. The motivation for doing this was to see if adequate structural performance is observed with the more flexible top plate, which has the advantage of using less lumber than a conventional top plate.

After assembling the bottom and side plates, bales were stacked in the formwork as shown in Figure 6. Bales were stacked in a running bond with 2.5 bales per course, for a total width of 2.6 m. The ½ bales were made by cutting the twine of a full bale and re-assembling, as shown in Figure 7. Walls 1 and 2 had 5 courses of on-edge bales for a total height of approximately 2.3 m, not including the top plate. Walls 3 to 5 had 6 courses of flat bales for a total height of approximately 2.1 m, not including the top plate.

Once the bales were stacked, the top plate was placed on top of the bales. Two nylon straps were threaded through holes cut in the top and bottom plates, as shown in Figure 8. The straps were then cinched down until the top plate was level. This usually required a number of iterations of tightening and then re-tightening straps as each side was leveled. Following compression, the walls with bales on-edge were 2100 mm high, and those with bales flat were 2025 mm high (again, not including the top plate).

Following precompression, Tenax mesh was affixed to Walls 8 and 10. The mesh was first stapled to the top and bottom plates, Figure 9(a). It was then pulled close to the bales by stitching the mesh with baling twine pulled through the bales, Figure 9(b).

The final step in the construction was the application of the plaster. This was done by hand, Figure 10(a), or by trowel. The initial layer was worked into the straw. Subsequent layers were built up until the plaster was visually judged to extend beyond the edge of the top, side, and bottom plates.

The plaster was then allowed to stand and cure in the laboratory. The air in the lab is generally kept constant at 20 °C. The cement plaster began to cure within a few hours. The clay plaster, however, could take several days to begin to dry and achieve strength. As a result, it was observed that the clay walls tended to slump by 50 to 75 mm below the top plate, as shown in Figure 11. This gap was closed when the side walls were removed before testing, however, the tension in the cinching straps was lost.

During the curing process, it was observed that shrinkage cracks developed on the surface of each wall. Clay plasters were observed to undergo much more cracking than the cement plasters. The cracks were not repaired before testing. Note that the usual practice in the field is to repair shrinkage cracks as they appear.

Once curing was complete (approximately 30 days after plastering was completed), the side walls were removed and the wall prepared for testing.

Test Set-Up and Instrumentation

The typical test set-up is shown in Figure 12. The walls were constructed under a steel loading frame. A movable hydraulic ram was mounted on the frame and used to apply compressive loads to the walls. The ram was operated using a hand-operated jack. A load cell was mounted to the ram. The load from the ram was distributed to the wall through a specially designed steel loading plate. Small steel box sections, Figure 12(c), were welded to the bottom of the loading plate every 600 mm. This simulates the load transfer through roof trusses to the top plate that will occur in a straw bale building.

Each test was monitored using a load cell and linear voltage displacement transducers (LVDTs) to measure deflections. Four LVDTs were mounted on each corner of the top plate, Figure 13(a), to measure the vertical deflections of the wall. Three LVDTs were mounted on the side of the plaster wall to measure lateral deflections, Figure 13(b). Two of these LVDTs were mounted approximately 300 mm from the top of the wall, with one at each end of the wall. The third LVDT was mounted mid-height, mid-length of the wall.

Each wall was constructed under the loading frame such that its long axis was aligned North-South. In the Results section, the LVDTs are identified using the nomenclature described in Figure 14.

Results

Load-Vertical Deflection

Figure 15 shows a typical load versus vertical deflection plot, in this case for Wall 4. The vertical deflections were measured by four linear voltage displacement transducers (LVDTs) on the corners of the steel bearing plate. For all of the load versus vertical deflection plots, the results are shown in a wide scale (Part (a) of each figure) for comparison between tests and in a close view so that details can be examined (Part (b) of each figure). Figure 15 shows that the response was fairly linear up to an applied load of 40 kN. In addition, all four LVDTs measured similar values up to 40 kN applied load. This indicates that the loading of the wall was uniform. As load is increased above 40 kN, the deflections on the south end of the wall increase much more rapidly than the north end as cracking initiates on this end of the wall. Finally, as the wall reaches its ultimate load at 56 kN, the load rapidly decreases and the deflection increases. At about 18 mm deflection, a plateau is reached which indicates that the load is being carried mainly by the straw due to the cracking of the plaster. At about 57 mm deflection, the load again increases. It is believed that the cracked plaster, still bonded to the straw, begins to interlock, allowing for this increase in capacity at this point.

For the most part, fairly uniform vertical loading was observed. Therefore, it is reasonable to average the values of the vertical LVDTs. Two exceptions are shown in Figure 16 and 17. In the case of Wall 2, shown in Figure 16, it can be seen that the SE and SW LVDTs were not properly secured and underwent slippage at about 5 kN. Therefore, these LVDT measurements were not included in the average vertical deflection plot that will be presented subsequently. In the case of Wall 5, it can be seen that as the loading was increased beyond 150 kN, the deflections appear to reverse and decrease. This is because the steel load plate began to bend, as shown in Figure 18, causing the ends to lift off the wall. The LVDT measurements were only included up to 150 kN in the average vertical deflection plot that will be presented subsequently.

Figures 19 to 28 show the load versus average vertical deflection for all ten walls tested. It should be noted that in Figure 19 (Wall 1) the maximum capacity of the load cell was reached at 115 kN, causing the plateau observed for this test. The ultimate load for this test was therefore not captured. In subsequent discussion, the ultimate load for this test will be taken as 115 kN. Also note that in Figure 20 (Wall 2), the load was increased to 25 kN, at which point the wall was unloaded and then reloaded.

It can be seen that in general, the load-deflection response of the walls before reaching the ultimate load consists of an initial non-linear response, followed by linear behaviour up to the ultimate load. For example, for Wall 1 (Figure 19), there is an initial rapid rise in deflection up to about 10 kN applied load. After this point, the wall becomes much stiffer (i.e., the slope of the curve increases) up to the ultimate load of 115 kN. This initial non-linear response can be attributed to bulging of the straw at the top of the wall which must first be compressed before the top plate begins to bear on the plaster skins.

After reaching the ultimate load, each wall exhibits a rapid increase in deflection and a loss of load as the plaster cracks. There are two types of post-failure behaviour observed, depending on whether cement or clay plaster is used. For walls with cement plaster (Walls 1, 12, 13), the peak load is followed by a steep reduction in load. For walls with clay plaster (Walls 2, 4, 6, 7) and one skin each of clay and cement plaster, the drop in load after failure is not nearly so dramatic. The reason is that the peak load before failure is governed primarily by the strength and stiffness of the plaster. Cement plaster is much stronger and stiffer than the clay plaster, leading to a much higher peak load. Following failure of the plaster, most of the strength of the wall is provided by the straw bales. As seen by the tests, the straw bales following plaster failure carry approximately 40 kN when the bales are flat (see Walls 3, 4, 7, 13) and approximately 20 kN when the bales are on-edge (see Walls 1, 2, 10, 12). The difference between the strength of the cement plaster and the bales is much more dramatic than the difference between the clay plaster and the bales.

Lateral Deflections

Lateral deflections were measured by LVDTs at the top and mid-height of each wall. The lateral deflections at the top of the walls are given in Figures 29 to 38. In Figure 29 (Wall 1), there is evidence that the LVDTs underwent slippage at about 25 kN of loading. Therefore, these results will not be considered in the remaining discussion. For the remaining walls, there are two typical behaviours observed. For Walls 3, 4, 7, and 10 the lateral deflections at the top of the wall remain zero (or very close to zero) until the ultimate load is reached. At this point, the lateral deflections increase rapidly. For Walls 2, 5, 6, 8, and 9 the deflections increase as the load increases. This indicates that these walls are not perfectly straight, causing the wall to bend and deflect laterally as load is applied. In addition, for Walls 2, 5 8, and 9 the deflections at the North and South ends of the walls are not equal as the load increases. This indicates that the top of these walls is also twisting as load is being applied.

The lateral deflections at the mid-height of the walls are given in Figures 39 to 48. For most of the walls (Walls 1, 2, 4, 6, 7, 8, 9, 10) the lateral deflections increase as the load is increased. This indicates that these walls are not perfectly straight, causing the wall to bend and deflect laterally as load is applied. In comparing the lateral deflections at the top of the walls, it can be seen that for Walls 4, 7, and 10 (Figures 32, 35, 38) there were no lateral deflections until the wall reached its ultimate load. Thus, these walls tended to bend in a “pinned-pinned beam” mode shape. On the other hand, lateral deflections at the top of Walls 1, 2, 6, 8, and 9 were observed as load was applied to these walls. This indicates that these walls tended to bend in a “cantilever beam” mode shape. Finally, mid-height lateral deflections of close to zero up to the ultimate load were observed for Walls 3 and 5. Wall 3 had lateral deflections at the top of the wall close to zero up to the ultimate load (Figure 31). Thus, Wall 3 was subjected essentially to uniform vertical loading with very little bending. Wall 5 had small lateral deflections at the top (Figure 33). Thus, it is subjected to a state close to uniform vertical loading but with some bending occurring in the upper half of the wall.

To summarize, in general the walls with bales laid flat (Walls 3, 4, 5, 7, 10) tended deflect uniformly or to bend in a "pinned-pinned beam" mode shape. The bales with bales laid on-edge (Walls 1, 2, 6, 8) tended to bend in a "cantilever beam" mode shape. The one exception was Wall 9, which had bales laid flat but tended to bend in the "cantilever beam" mode shape.

Failure Modes

Figures 49 to 58 show each wall following failure. It should be noted that in no instance did any of the walls fail in a catastrophic manner. Failure was typically preceded by widespread cracking of the plaster. Following failure, each wall remained standing and as described previously had significant post-failure capacity. Typically tests were terminated not because of collapse but because LVDTs had run out of stroke for measuring deflections.

Walls 1, 2, 6, and 8, which had bales stacked on-edge, generally failed by bending laterally and buckling. In the case of Wall 1 (Figure 49(a)), this was accompanied by debonding of the plaster from the straw.

Walls 3, 4, 5, 7, 9, and 10 had bales stacked flat and generally failed by vertical crushing and accompanied by much less lateral bending.

An exception was Wall 5 (Figure 53). In this case, failure was initiated as the steel top plate underwent bending due to insufficient stiffness. This causes a concentration of load at the center of the timber top plate, causing it to fail by crushing and splitting. In turn, there was localized crushing of the cement plaster adjacent the timber top plate.

Another exception was Wall 10 (Figure 58) for which large lateral deflections following failure were observed. This can be related to the presence of Tenax mesh. The mesh bridged the cracks following failure and allowed the wall to continue to deflect laterally even after buckling occurred.

Variations in Plaster Thickness

Figures 59 to 63 are contour plots based on the plaster thicknesses measured following testing for Walls 6 to 10. For all of the walls, the nominal thickness of the plaster was 25 mm on each side. The actual thickness varies between 15 mm and 60 mm. In the case of Wall 8 (Figure 61) the east-side has a plaster thickness that is almost uniformly less than 25 mm. This wide variation in plaster thickness can be attributed to the variation in bale dimensions. It means that the plaster is not being used effectively, as cracking and failure will tend to initiate where the thickness is smallest.

Discussion

Table 4 summarizes the results of the tests. The table indicates the ultimate load for each test as well as the plaster strength as determined from three 50 mm x 50 mm x 50 mm cube tests of the plaster on the day that the wall was tested. For Wall 3, which had one clay plaster skin and one cement plaster skin, strength values for both plasters were measured, with the smaller value being the clay plaster strength.

The table also includes the average, maximum, and minimum measured plaster thicknesses for Walls 6 – 10. The average plaster thickness is the average of all the plaster thicknesses measured for a given wall. The plaster thicknesses for Walls 1 – 5 were not measured. However, the average values for the other walls were calculated and have been used in the table as an estimate of the plaster thickness.

Note that for all of the walls the nominal plaster thickness was 25 mm. The average plaster thickness for each wall is 20% to 64% larger than this value, except for Wall 8, which is 4% less. Of greater interest, however, is the range of plaster thicknesses. It would be expected that the wall would tend to fail where the plaster thickness is at a minimum. The measured minimum thickness values ranged from 20% to 68% less than the nominal plaster thickness. On the other hand, the maximum measured plaster thicknesses were between 2.5 and 4.2 times thicker than the nominal plaster thickness. Given that the wall should tend to fail where the plaster thickness is a minimum, the maximum thickness is a measure of the excess plaster that does not contribute to the strength of the wall.

One of the reasons it is difficult to compare straw bale test results in the literature is that often critical parameters such as plaster strength and thickness are not reported. In Table 4, the ultimate load was divided by the total area of plaster, using the minimum plaster thickness and the width of plaster skin of 2440 mm. The result is the ultimate stress. Theoretically, if the wall is subjected to simple vertical compression, the ultimate stress should be equal to the strength of the plaster. The ratio of the measured ultimate stress to plaster strength is given in the last column of Table 4. This is a more rational means of comparing the strength of the walls than simply comparing the ultimate load. Clearly, except for Wall 4, the strength of the walls falls well below what would be expected based on the strength of the plaster.

Leaving aside Wall 1 (for which the true ultimate load was not measured because it exceeded the load cell capacity) and Wall 5 (for which the timber top plate failed prematurely), the strength of the cement plaster walls ranges between 8% and 18% of the theoretical strength. The strength of the clay plaster walls ranges between 50% and 102% of the theoretical strength. Wall 4 is slightly stronger (by 2%) than the plaster strength but this is well within the variation observed for the plaster strengths and the error in measuring the plaster thickness. It should also be noted that the minimum plaster thickness for this wall is an estimate based on the measurements of Walls 6 to 10.

These results indicate that, from a structural point of view, conventional straw bale construction does not make efficient use of plaster. Large amounts of plaster may be applied to the wall that do not contribute in an efficient way to the strength of the wall. This can be attributed to the variations in bale dimensions and the method of hand applying the plaster. It is difficult to plumb a straw bale wall because of the bale variations, and this leads to bending of the wall that will reduce its strength from its theoretical value. From an environmental point of view, it would be beneficial to use cement-lime plaster sparingly. These results suggest that straw bale builders may want to consider more quality control (trimming bales to reduce variation, using formwork to get a consistent plaster thickness, ensuring walls are plumb) in the construction of the walls to address these issues. This will of course result in more labour in the construction, but if cement-lime plaster must be used, it will ensure it is used in a much more efficient and therefore environmentally-friendly manner.

In general, the clay plaster walls have a lower strength than cement-lime plaster walls because the plaster strength is lower. The average strength of the cement-lime plasters was 22 MPa and the average strength of the clay plasters was 0.8 MPa. Thus, on average the cement lime plasters are 27 times stronger than the clay plasters. However, of more practical importance is the strength the walls are able to achieve. The average strength of the walls with cement-lime plaster was 3.3 MPa, while the average strength of the walls with clay plaster is 0.5 MPa. Thus, the cement-plastered walls, as built, were 6.6 times stronger than clay plaster walls.

This point is further reinforced by examining the ratio of measured to theoretical wall strength in Table 4. The clay plaster walls reach a much higher percentage of their theoretical strength than the cement-lime walls. One reason for this appears to be the susceptibility of cement-lime plaster to local buckling and debonding (see Figures 49 and 57 and the Results – Failure Modes discussion), likely because of the high stiffness of this material compared to clay plaster.

Another important parameter for the strength of straw bale walls is the orientation of the bales. The results indicate that bale orientation has an impact on wall strength when clay plaster is used, but not if cement-lime plaster is used. Walls 1 and 8 were cement-lime plastered with bales on-edge, and had ratios of measured to theoretical strengths of 17% and 16% respectively. Note that the actual ultimate load for Wall 1 was not measured and Wall 8 had Tenax mesh. Walls 5, 9, and 10 were cement-lime plastered with bales flat, and had ratios of measured to theoretical strengths of 18%, 18%, and 8% respectively. Note that Wall 5 experienced top plate failure and Wall 10 had Tenax mesh. Based on these results, it does not appear there is a statistically significant difference in the compressive strength of cement-lime plastered walls with on-edge or flat oriented bales. Wall 10 does appear to have a strength significantly lower than the other walls, however, this appears to be an outlier. Upon inspection of the plaster after failure, it was found that the Tenax mesh had actually been a barrier to allowing good bond between the plaster and straw.

Walls 2 and 6 were clay plastered with bales on-edge, and had ratios of measured to theoretical strengths of 53% and 50% respectively. Note that Wall 6 had clay slip applied to the straw before plastering. Walls 4 and 7 were clay plastered with bales flat, and had ratios of measured to theoretical strengths of 102% and 59% respectively. Note that Wall 7 had clay slip applied to the straw before plastering. Based on these results, the walls with bales laid flat are stronger than those on-edge. On average, the ratio of measured to theoretical strength for the on-edge bales was 52% and for the flat bales was 81%.

The effect of using Tenax mesh on the compressive strength of cement-lime plastered walls can be examined by comparing Walls 5 and 9, which had bales oriented flat and had no Tenax mesh, to Wall 10, which had bales oriented flat and Tenax mesh. Walls 5 and 9 both had a ratio of measured to theoretical strength of 18%, while Wall 10 had a ratio of measured to theoretical strength of 8%. A similar effect was seen for walls with bales oriented on-edge. Wall 1, with no Tenax mesh, had a measured to theoretical strength ratio of 17%, while Wall 8, with Tenax mesh, had a measured to theoretical strength of 16%. Thus, the application of Tenax mesh actually reduced the wall strength rather than improved it. This can be attributed, as discussed above, to the tendency of poor plaster-to-straw bonding when Tenax is used, which in turns appears to lead to local buckling controlling the wall failure.

It should be noted that although the Tenax mesh does not improve the compressive strength of straw bale walls, it certainly improves the ductility of the wall following failure, as noted in the Results, permitting the wall to undergo very large lateral deflections without debonding of the plaster. This is certainly a benefit if the wall needs to be designed to resist large seismic loads.

The effect of applying clay slip can be examined by comparing Wall 4 which had bales oriented flat and no clay slip, to Wall 7, which had bales oriented flat and clay slip applied. The measured to theoretical ratio for Wall 4 was 102%, while for Wall 7 it was 59%. A similar effect was seen for walls with bales oriented on-edge. Wall 2, with no clay slip, had a measured to theoretical ratio of 53%, while Wall 6, which had clay slip, had a measured to theoretical ratio of 50%. Thus the application of clay slip did not improve compressive strength. It should be noted that there may be other reasons for applying clay slip, such as easing the application of wet clay to the straw surface.

Conclusions

The results of ten compressive tests of full-scale straw bale walls using conventional straw bale building techniques have been presented. The effect of various plasters, bale orientations, and meshes on compressive strength were examined.

The following conclusions follow from this work:

1) Straw bale walls with cement-lime plasters have ultimate strengths of, on average, 3.3 MPa, and ranging between 1.9 MPa and 5.6 MPa.
2) Straw bale walls with clay plasters have ultimate strengths of, on average, 0.5 MPa, and ranging between 0.3 MPa and 1.0 MPa.
3) The measured strength of the cement plaster walls ranges between 8% and 18% of the theoretical strength. The low strength of these walls compared to the theoretical value appears to be related to local buckling of the very stiff plaster.
4) The measured strength of the clay plaster walls ranges between 50% and 102% of the theoretical strength.
5) Bale orientation has little effect on the compressive strength of a wall if cement-lime plaster is used.
6) Walls with bales oriented flat are about 56% stronger than walls with bales oriented on-edge when clay plaster is used.
7) Tenax mesh does not improve the compressive strength of straw bale walls with cement-lime plaster, and in fact may decrease the strength by affecting the plaster-straw bond and leading to premature local buckling of the plaster. The mesh does, however, improve the ductility of the wall to lateral deflections after compressive failure has occurred.
8) Clay slip does not improve the compressive strength of straw bale walls plastered with clay plaster.
9) Because of the wide variation of plaster thickness when hand plastering is used, the plaster is not being used efficiently from a structural point of view. Especially when environmentally unfriendly plasters such as cement-lime are used, builders should consider methods of applying the plaster so that the thickness is uniform, and ensuring the walls are plumb.

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Table 1 – Masses of typical bales used in the wall construction.

	Walls 1 -5 (kg)	Walls 6 – 10 (kg)
	13.52	18.74
	13.76	20.99
	12.09	19.23
Average	13.1	19.1
St. Dev.	0.9	1.2

Table 2**:** Plaster mix proportions by mass.

Plaster Type	**Sand**	**Clay**	**Mason's Cement**	**Water**	**Straw**
Clay	5.7	3.5	0	1	*
Cement	4.4	0	0.9	0.9	0

* Approximately 5 L of loose straw was added to the mix.

Table 3 – Configuration of walls tested.

Wall	Plaster	Bale Orientation	Number of courses	Mesh	Dates constructed	Date Tested
1	Cement	Edge	5	None	Dec. 12 – 16, 2006	Jan. 19, 2007
2	Clay	Edge	5	None	Dec. 12 – 16, 2006	Feb. 1, 2007
3	Cement/Clay	Flat	5	None	Feb. 13 – 17, 2007	Mar. 26, 2007
4	Clay	Flat	6	None	Feb. 13 – 17, 2007	April 3, 2007
5	Cement	Flat	6	None	Feb. 13 – 17, 2007	April 12, 2007
6	Clay	Edge	5	Clay Slip	April 28 – May 2, 2007	July 19, 2007
7	Clay	Flat	6	Clay Slip	April 28 – May 2, 2007	July 31, 2007
8	Cement	Edge	5	Tenax	April 28 – May 2, 2007	Aug. 20, 2007
9	Cement	Flat	6	None	August 20 – 22, 2007	Sept. 26, 2007
10	Cement	Flat	6	Tenax	August 20 – 22, 2007	Oct. 3, 2007

Table 4 – Summary of test results.

Test #	Bale Orientation	Plaster Type	Reinforcement	Cube Strength (MPa) - avg. of 3	Ultimate Load (kN)	Lateral Deflection (mm)	Location	Thickness (mm) Average	Max	Min	Ult. Stress (MPa)	Mea/Theo
1	Edge	Cement-Lime	None	11.3	110.23	1.1	mid/top	35	79	12	1.9	17%
2	Edge	Clay	None	0.8	25.21	0.9	mid/bot	35	79	12	0.4	53%
3	Flat	CL / Clay	None	1.0 / 18.5	40.78	0.9	mid/top	35	79	12	0.7	70 / 4 %
4	Flat	Clay	None	1.0	57.26	9.0	mid	35	79	12	1.0	102%
5	Flat	Cement-Lime	None	18.5	190.58	11.0	top	35	79	12	3.3	18%
6	Edge	Clay	Clay Slip	0.7	20.47	3.0	top	30	62	12	0.3	50%
7	Flat	Clay	Clay Slip	0.7	40.18	4.5	top	38	106	20	0.4	59%
8	Edge	Cement-Lime	Tenax	20.3	127.24	11.0	mid	24	69	8	3.3	16%
9	Flat	Cement-Lime	None	30.5	217.42	4.0	top	41	80	8	5.6	18%
10	Flat	Cement-Lime	Tenax	30.7	156.81	7.0	mid	40	80	13	2.5	8%

* Thickness values for Walls 1 – 5 are the average of the average, maximum, and minimum values for Walls 6 – 10.
** Ultimate load for Wall 1 not measured.
*** Top plate for Wall 5 failed prematurely.

Figure 1 – Batching of materials prior to mixing plaster in mortar mixer.

Figure 2 – Tenax Cintoflex D mesh.

(a) (b)

Figure 3 – Preparation and application of clay slip: (a) pouring slip from mixer; (b) applying slip to bale.

Figure 4 – Assembly of formwork

All dimensions mm.

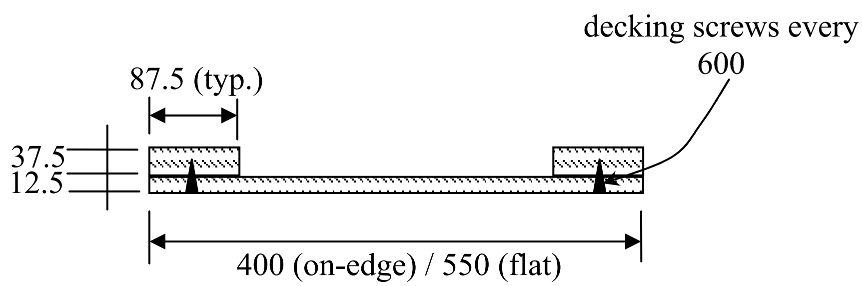


Figure 5 – Cross-section of top and bottom plates.

Figure 6 – Stacking bales in the formwork.

Figure 7 – Re-tying half bales.

(a) (b)

Figure 8 – Precompressing straw wall: (a) Nylon strap; (b) Ratchet tool.

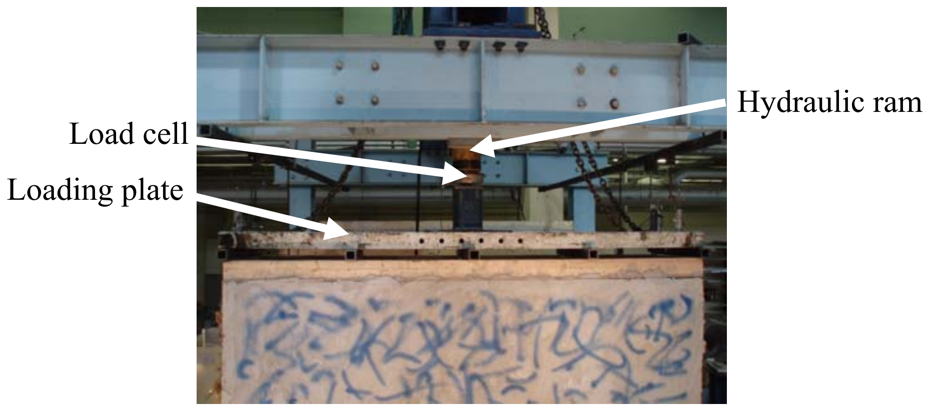
Figure 9 – Affixing Tenax mesh: (a) Stapling to top plate; (b) Stitching to bales.

(a) (b)

Figure 10 – Application of plaster: (a) Initial layer; (b) Final layer.

Figure 11 – Slumping of clay plaster wall.

(a)



(b)

(c)

Figure 12 – Test set-up: (a) Overall view; (b) View showing hydraulic ram, load cell, and load plate; (c) Close-up of load plate.

Figure 13 – LVDTs: (a) On top plate to measure vertical deflections; (b) On plaster skin to measure lateral deflections.

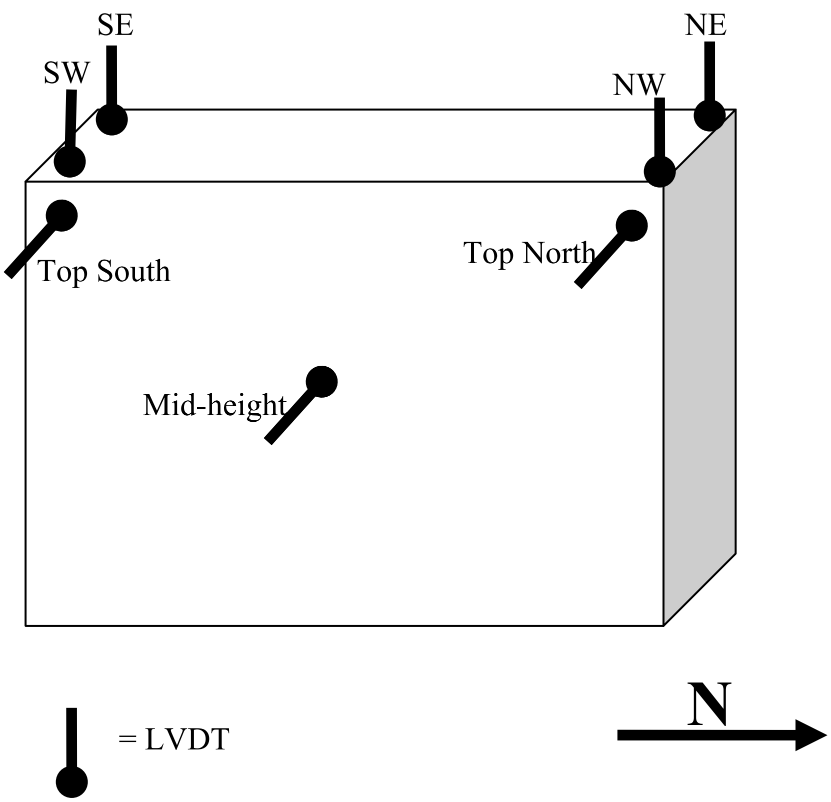
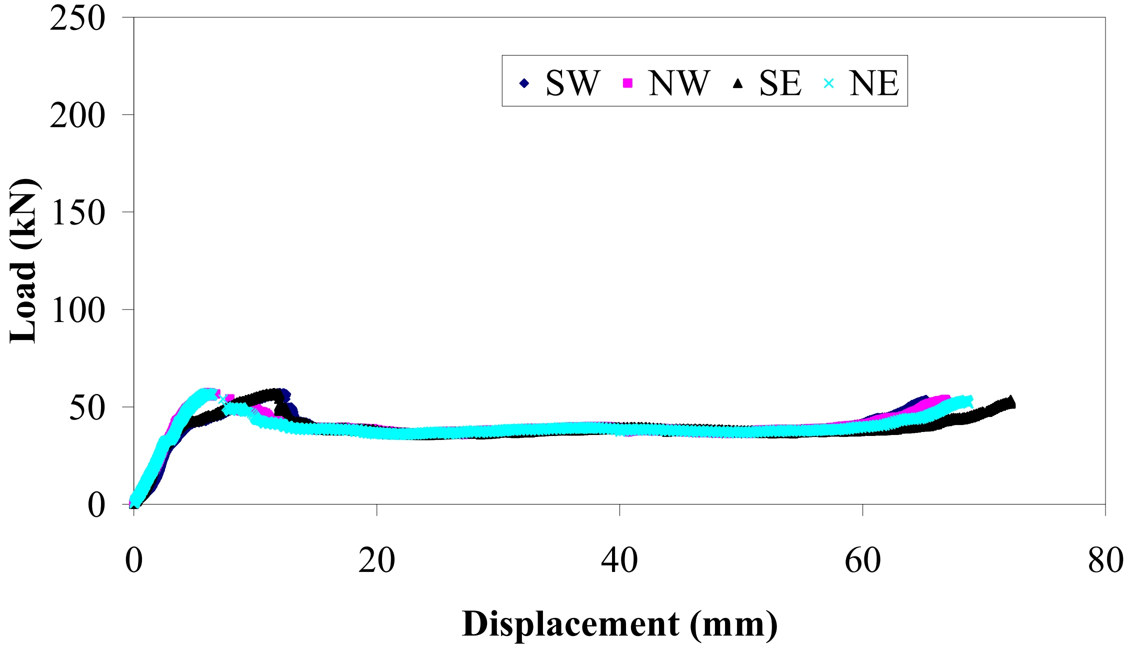


Figure 14 – Nomenclature for LVDTs.



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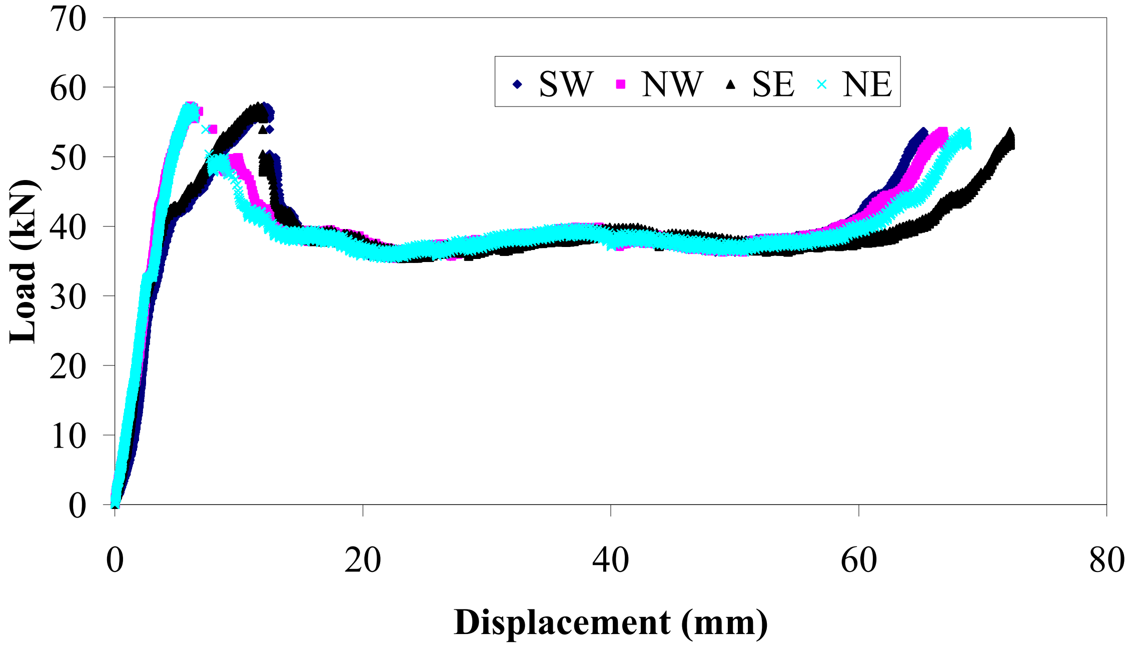
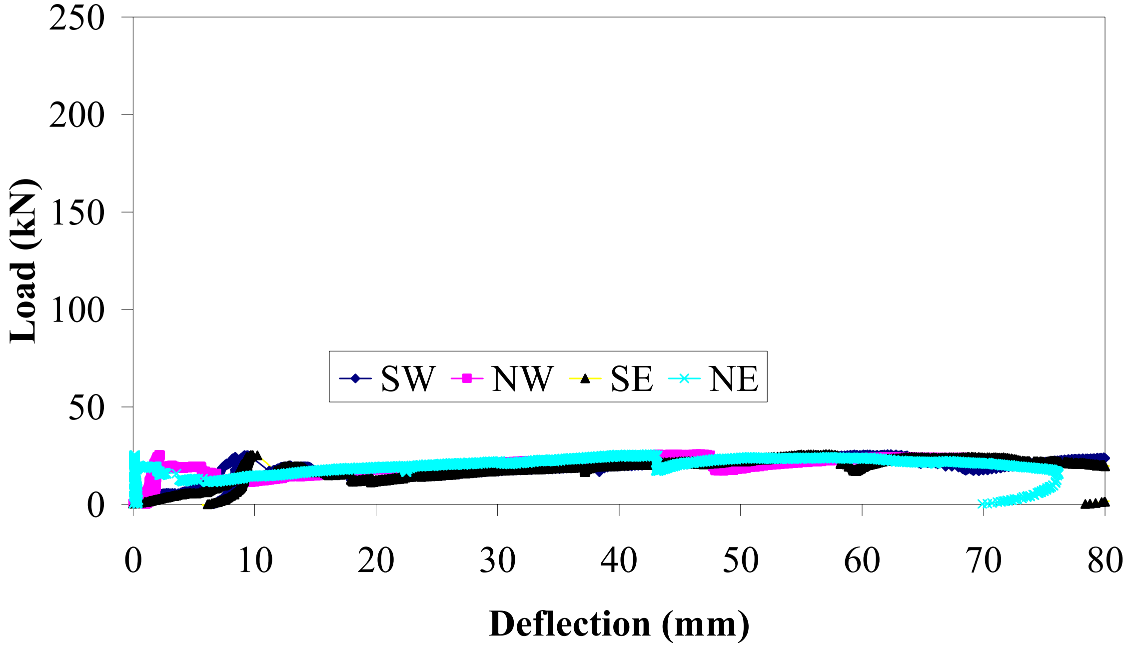


(b)

Figure 15 – Load versus vertical displacement for Wall 4 (clay plaster, bales flat).



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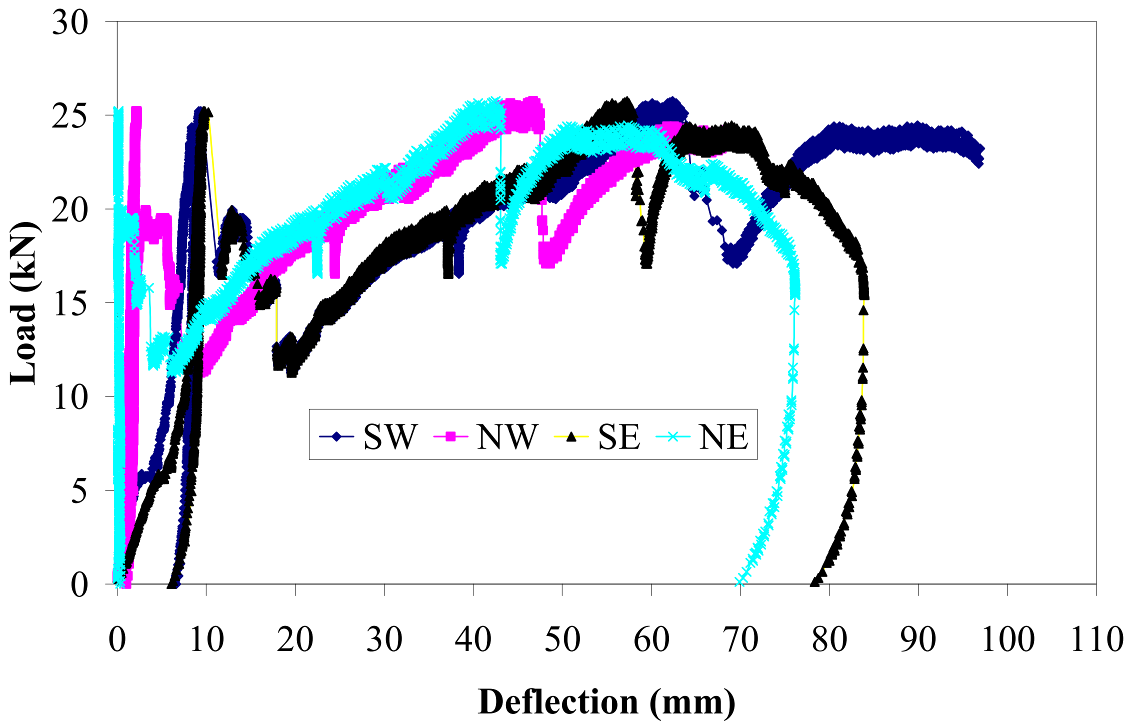
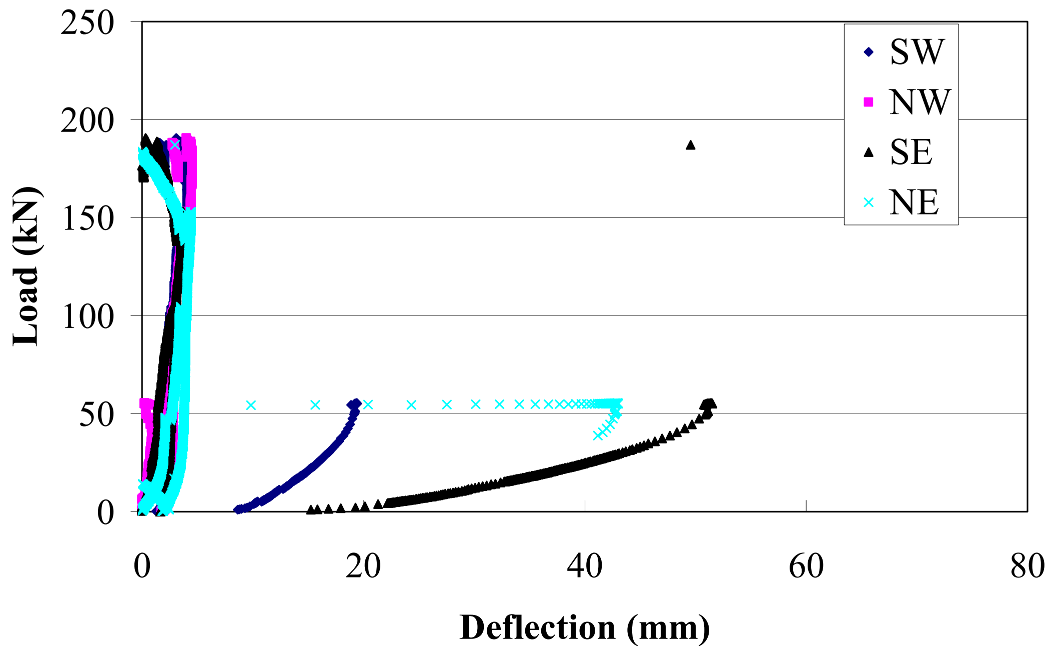


(b)

Figure 16 – Load versus vertical displacement for Wall 2 (clay plaster, bales on-edge).



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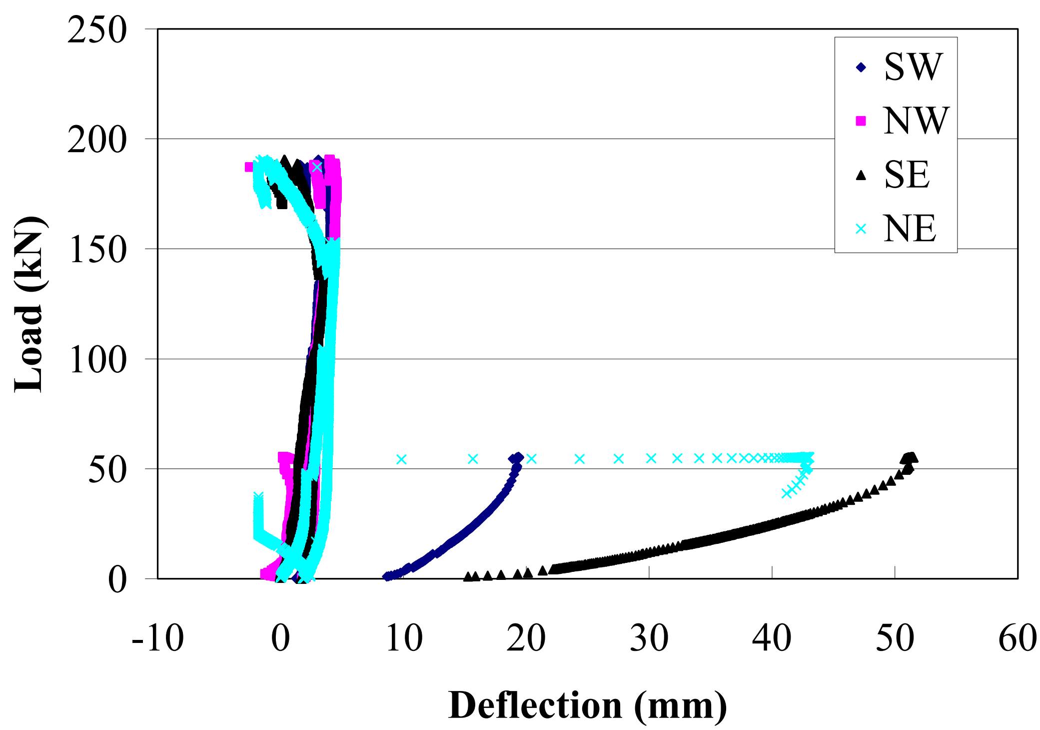
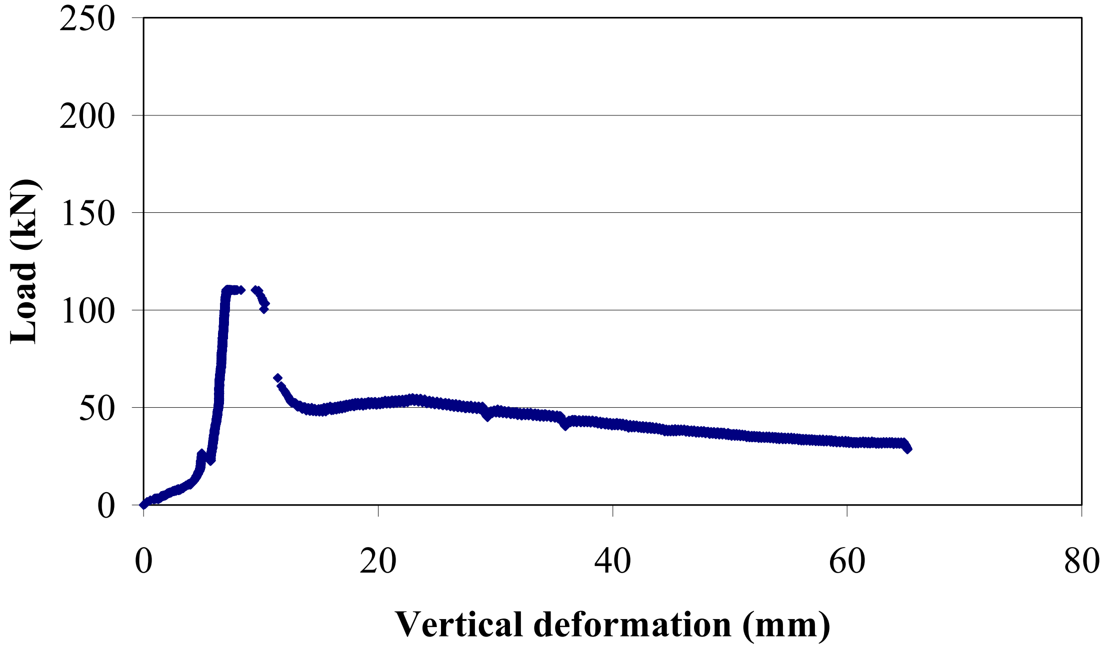


(b)

Figure 17 – Load versus vertical displacement for Wall 5 (cement plaster, bales flat).

Figure 18 – Steel beam bending and lifting off timber top plate during loading of Wall 5.



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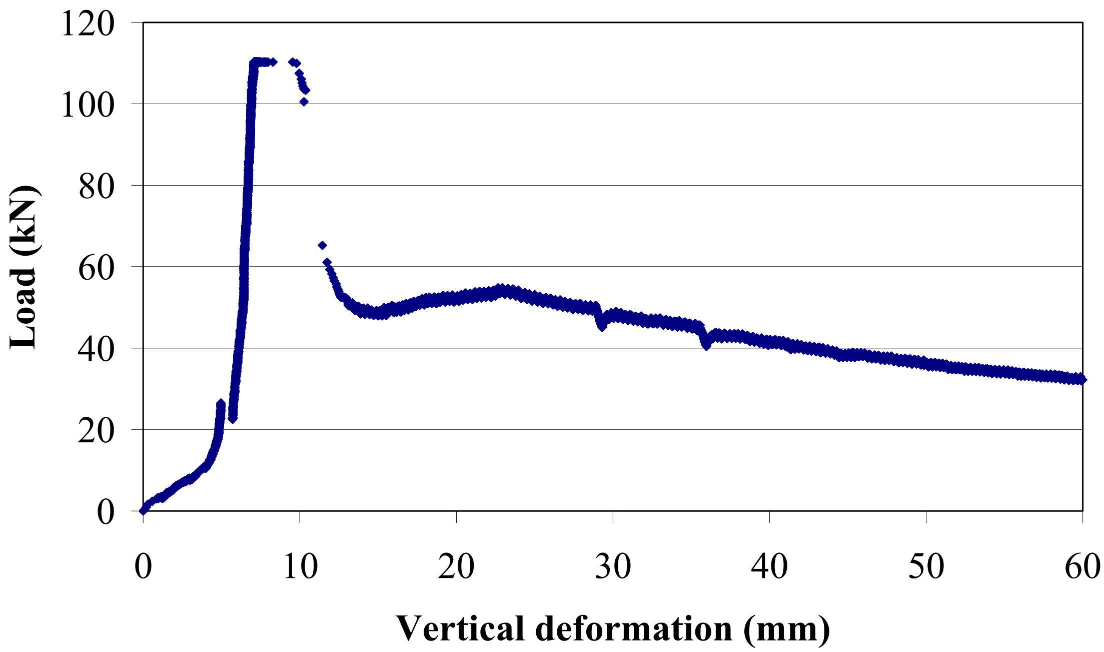
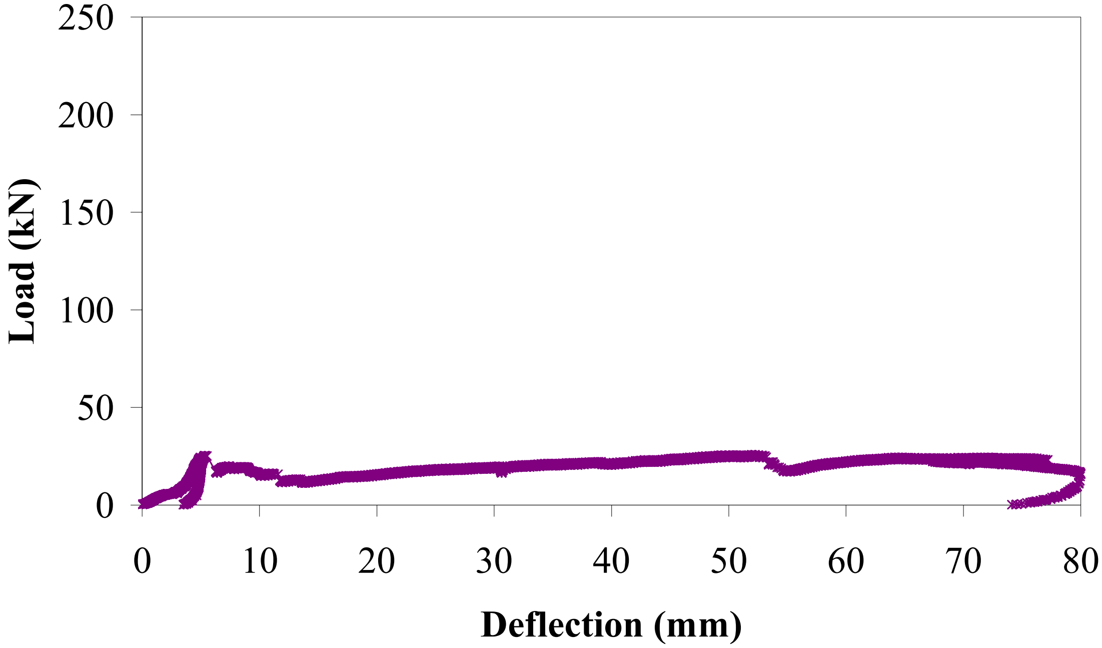


(b)

Figure 19 – Load versus average vertical displacement for Wall 1 (cement plaster, bales on-edge).



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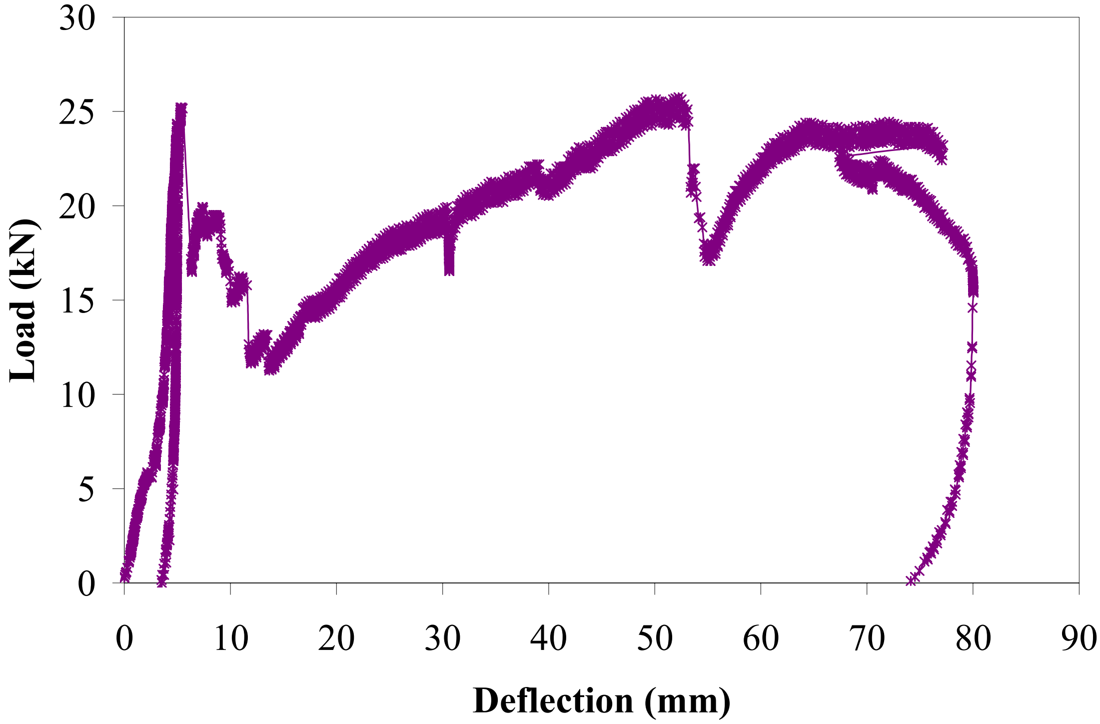
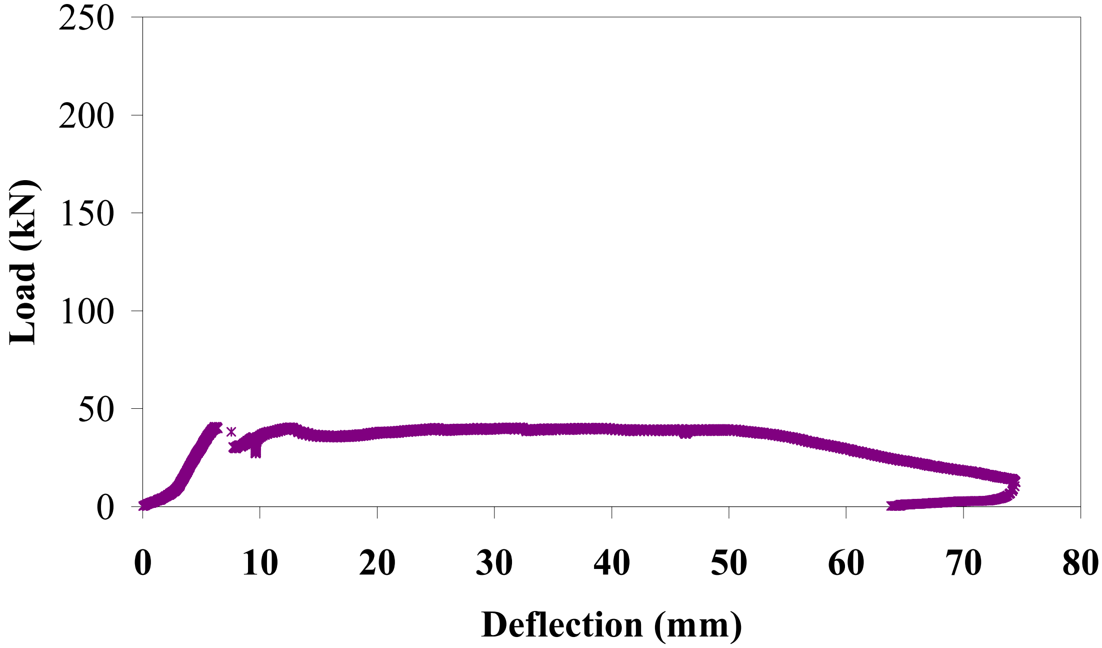


(b)

Figure 20 – Load versus average vertical displacement for Wall 2 (clay plaster, bales on-edge).



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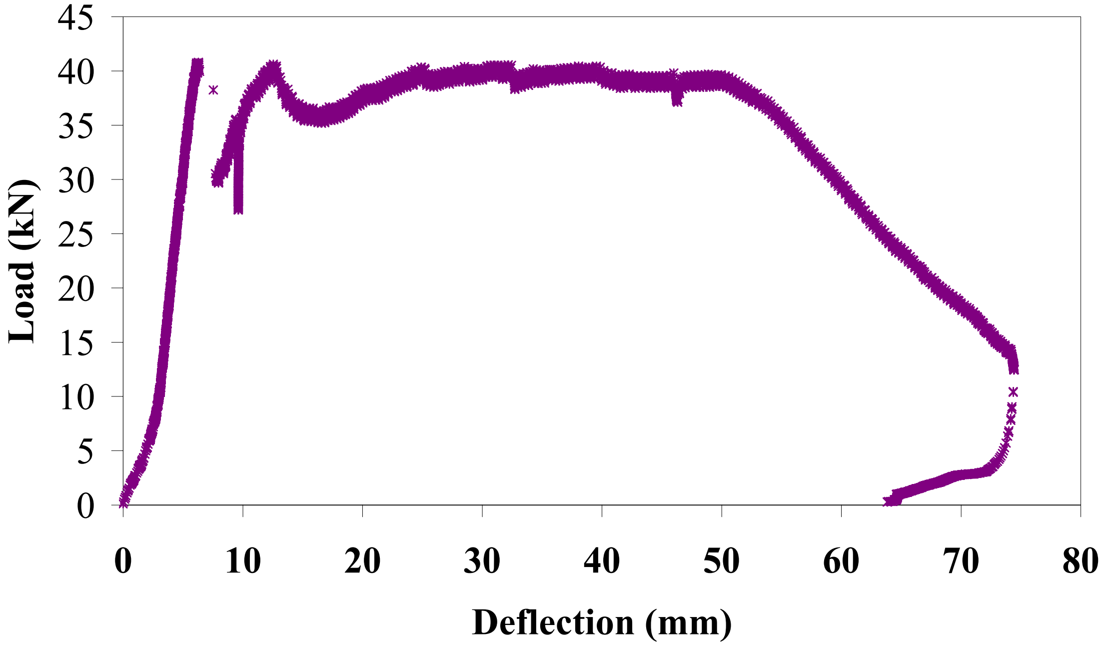
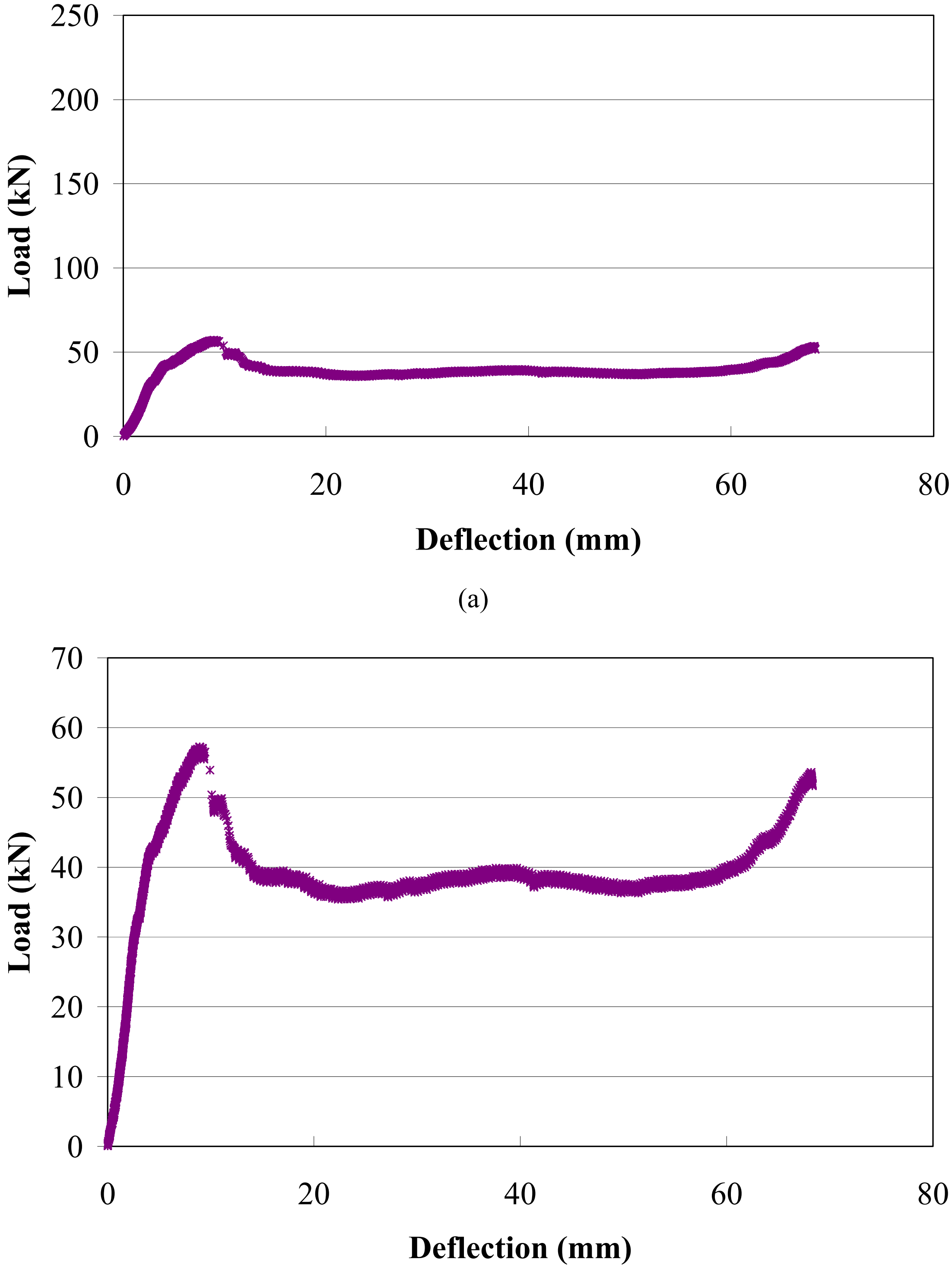


(b)

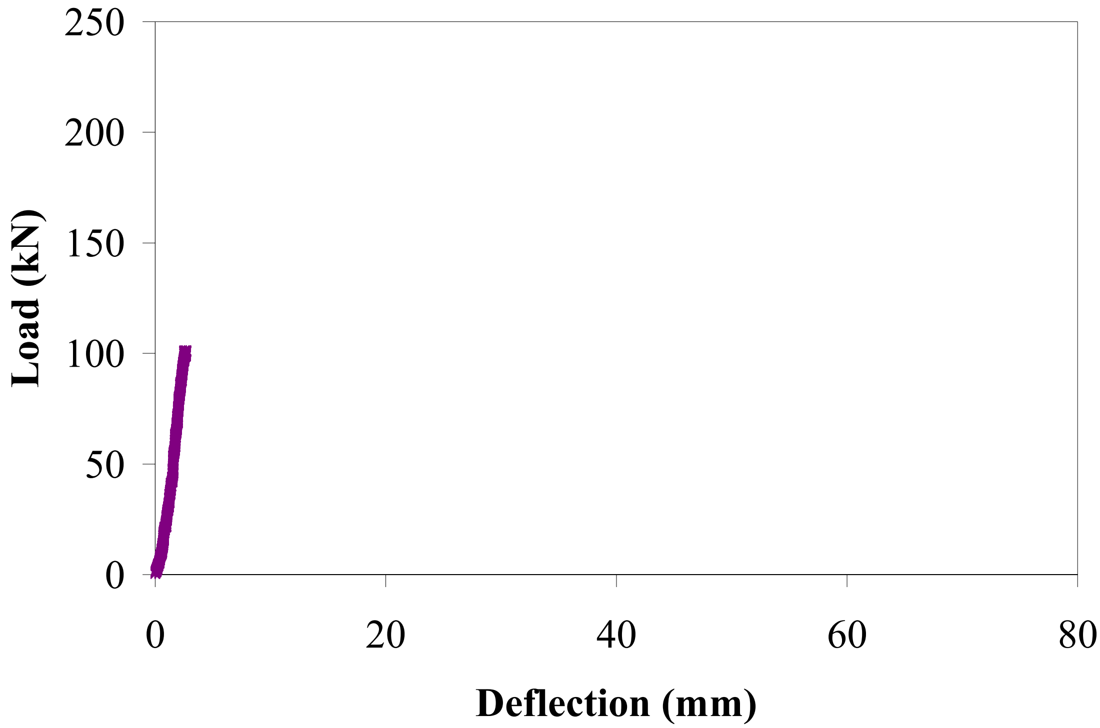
Figure 21 – Load versus average vertical displacement for Wall 3 (clay/cement plaster, bales flat).



(a)

(b)

Figure 22 – Load versus average vertical displacement for Wall 4 (clay plaster, bales flat).



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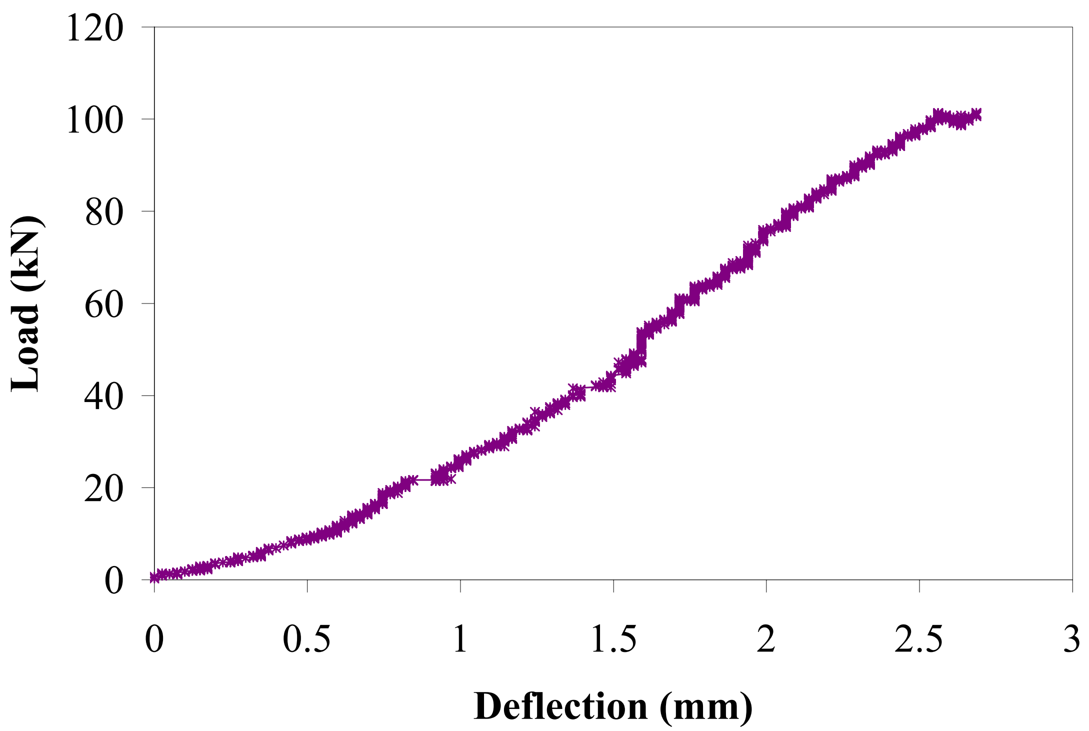
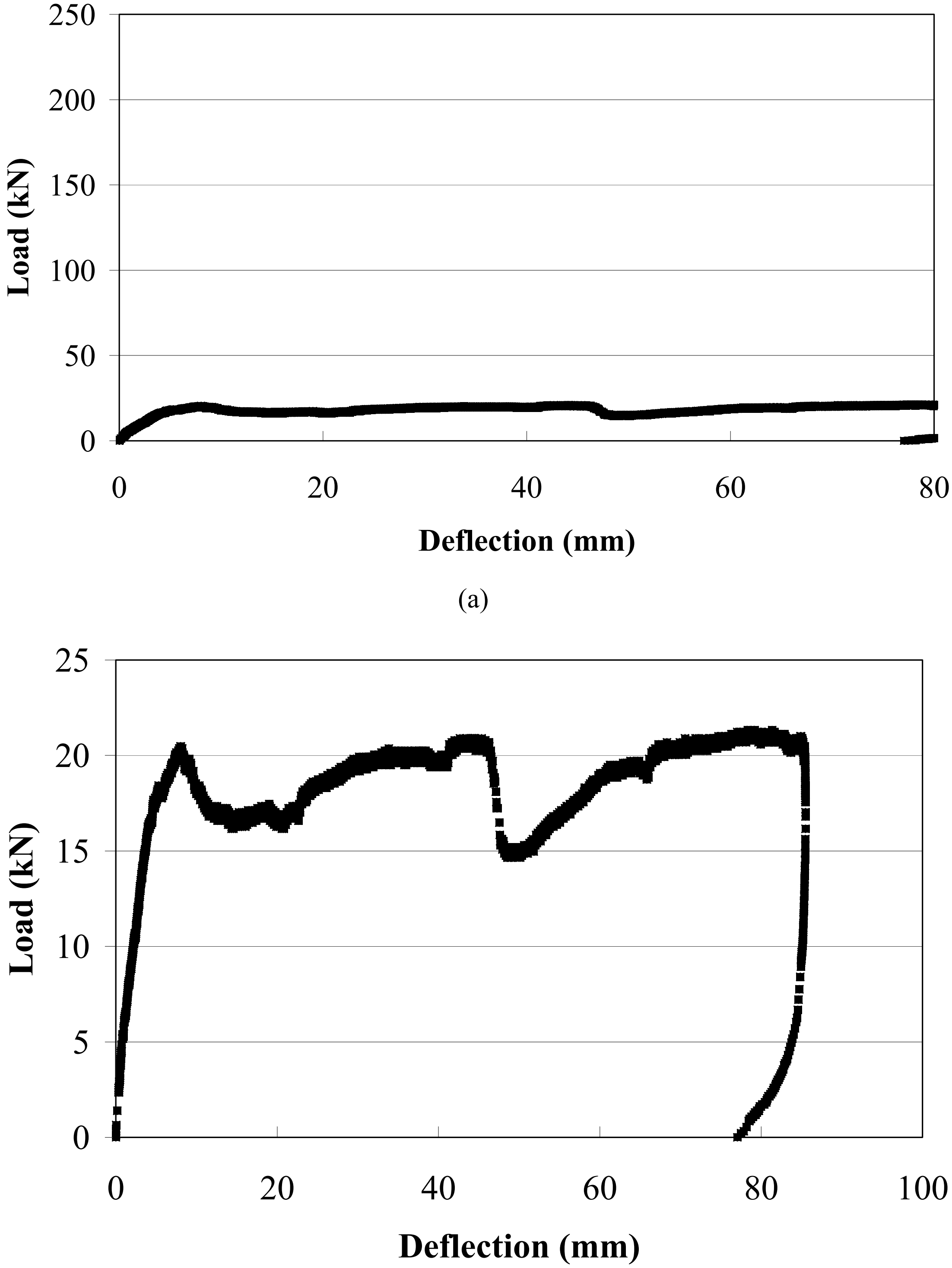


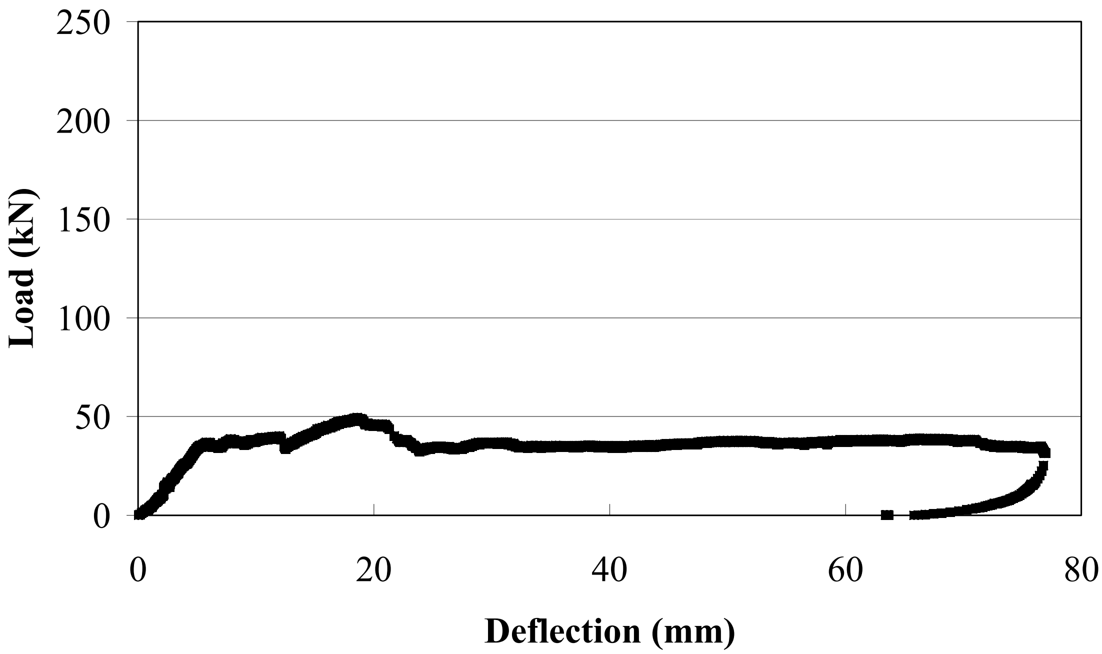
(b)

Figure 23 – Load versus average vertical displacement for Wall 5 (cement plaster, bales flat).



(b)

Figure 24 – Load versus average vertical displacement for Wall 6 (clay plaster, bales on-edge).



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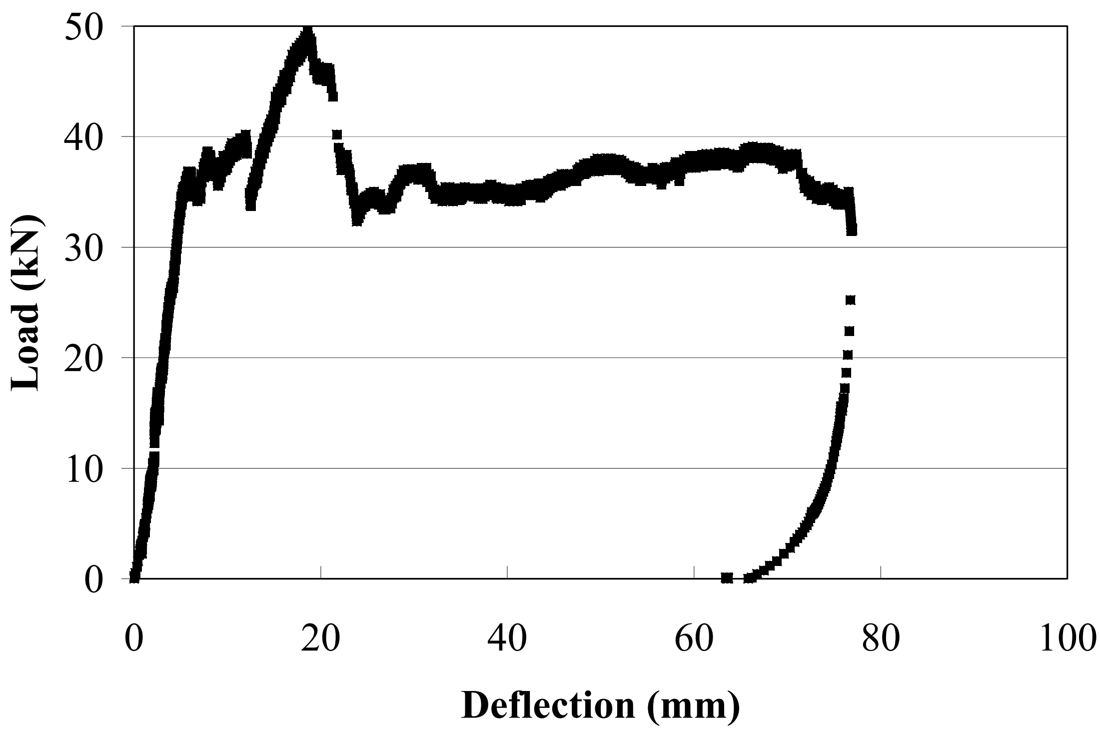
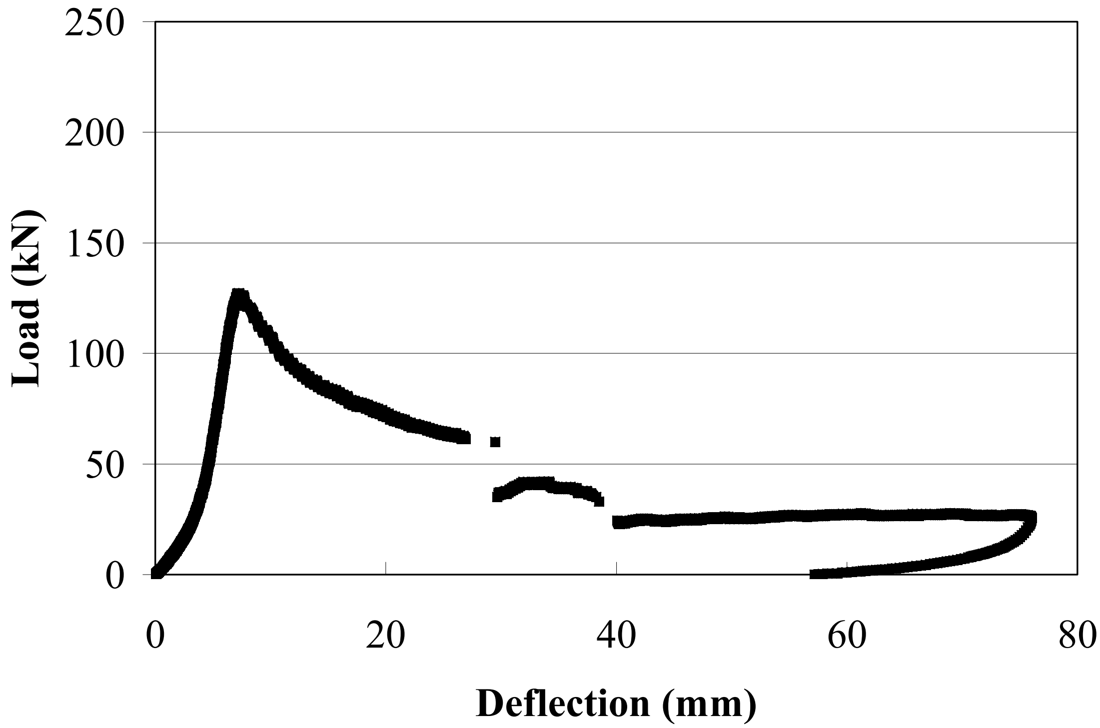


(b)

Figure 25 – Load versus average vertical displacement for Wall 7 (clay plaster, bales flat).



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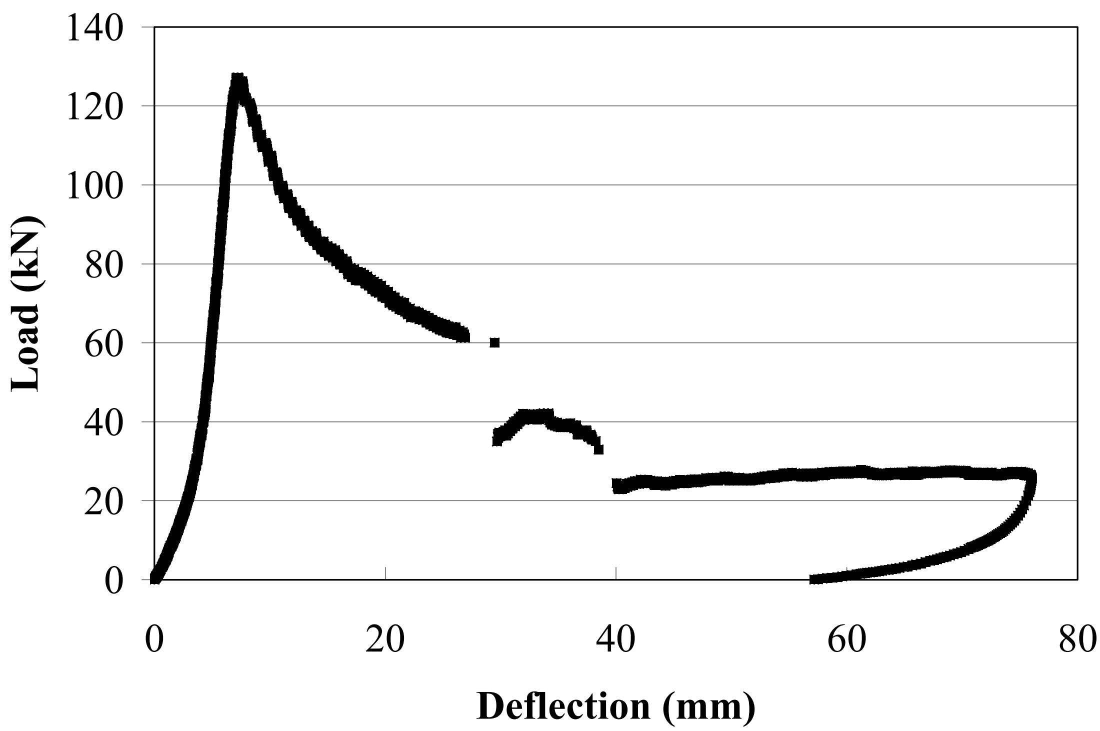
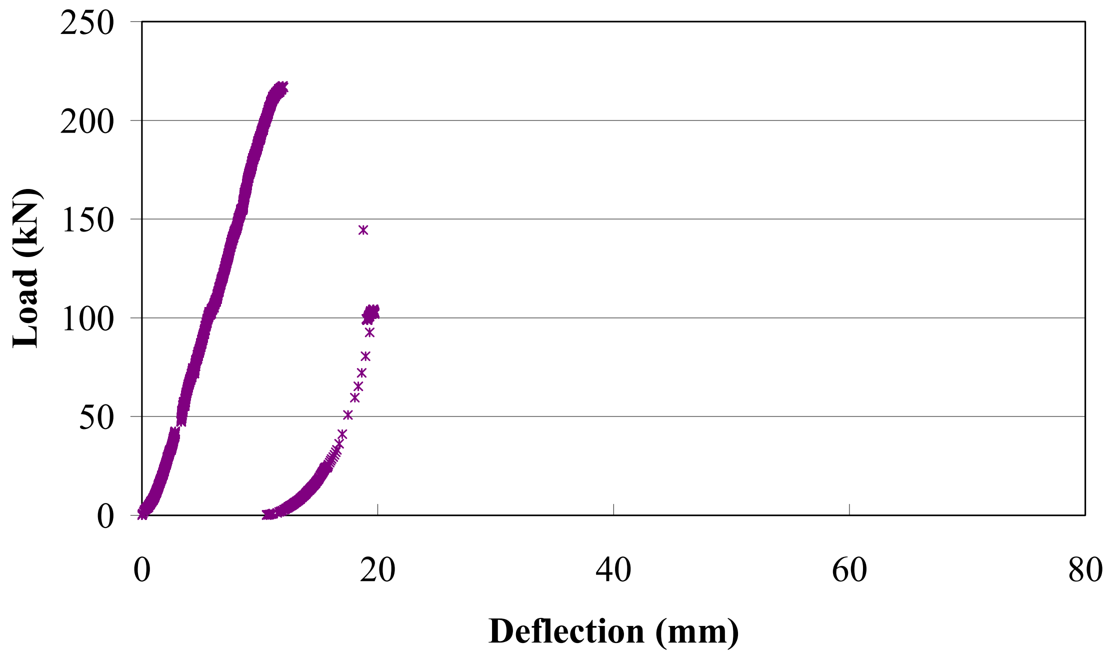


(b)

Figure 26 – Load versus average vertical displacement for Wall 8 (cement plaster, bales on-edge).



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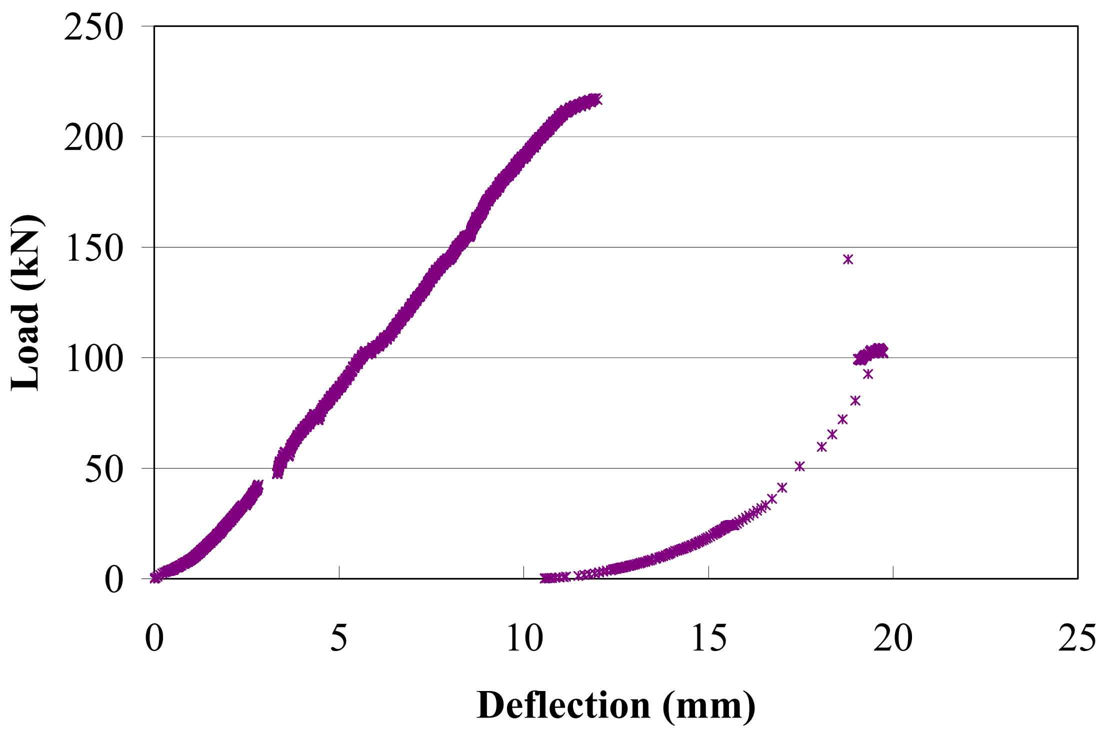
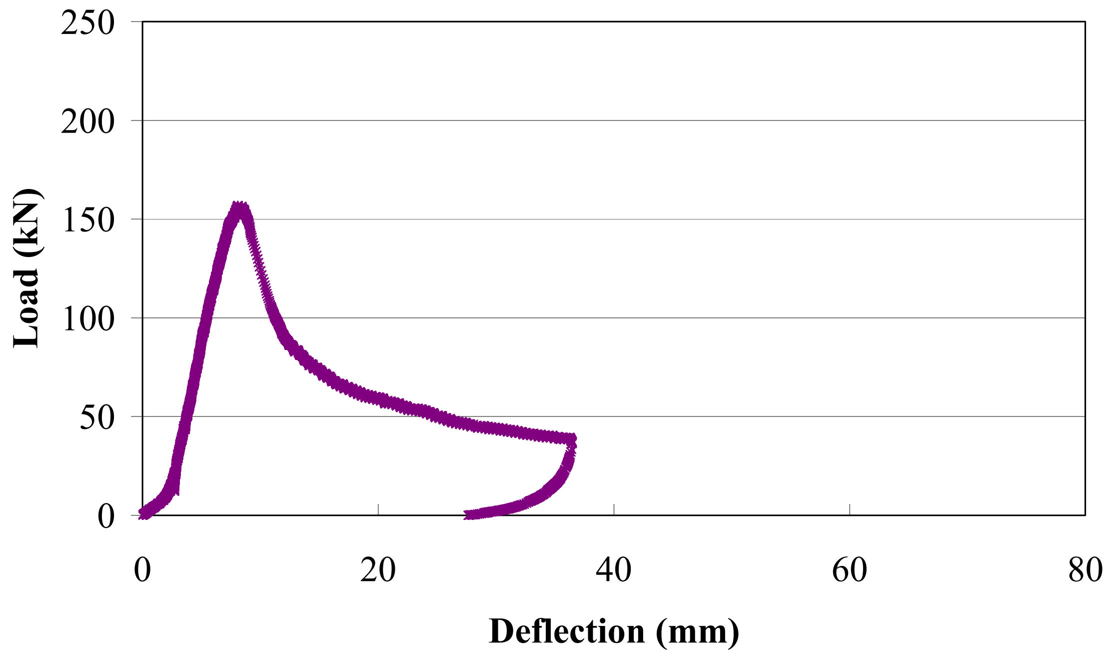
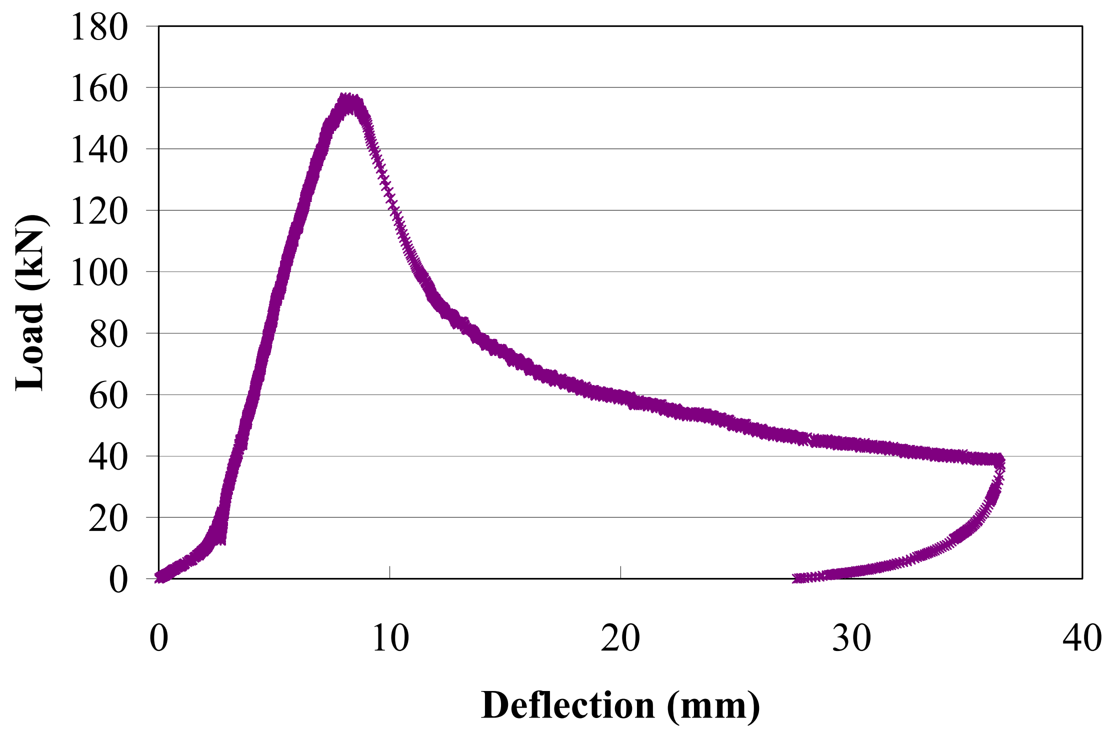


(b)

Figure 27 – Load versus average vertical displacement for Wall 9 (cement plaster, bales flat).



(a)



(b)

Figure 28 – Load versus average vertical displacement for Wall 10 (cement plaster, bales flat).

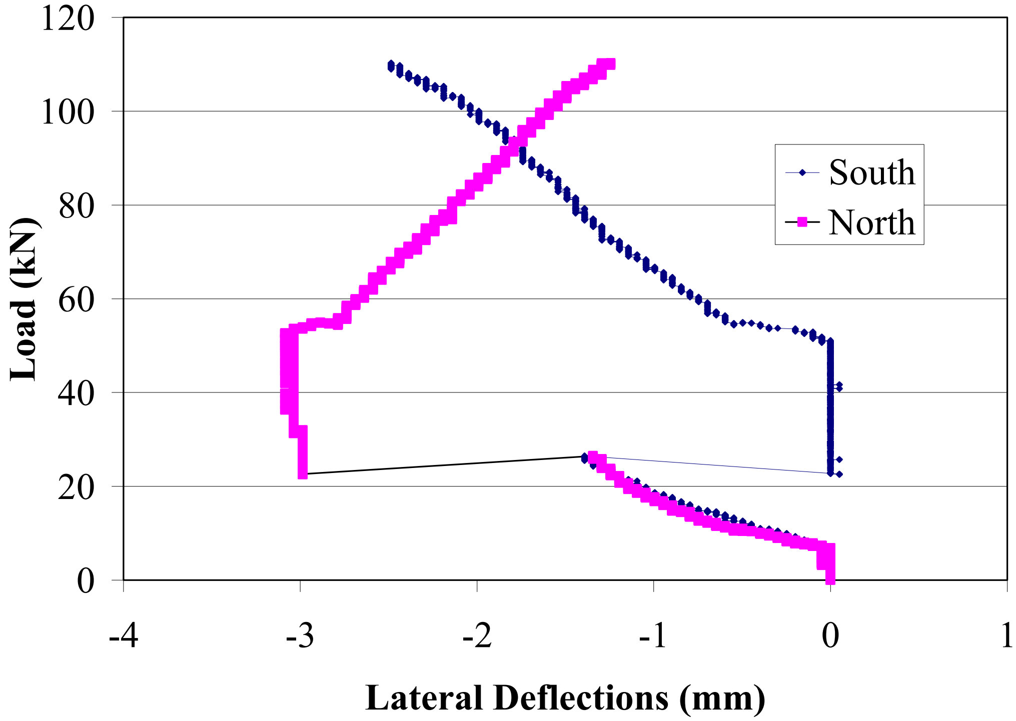


Figure 29 – Lateral deflections at the top of Wall 1 (cement plaster, bales on-edge).

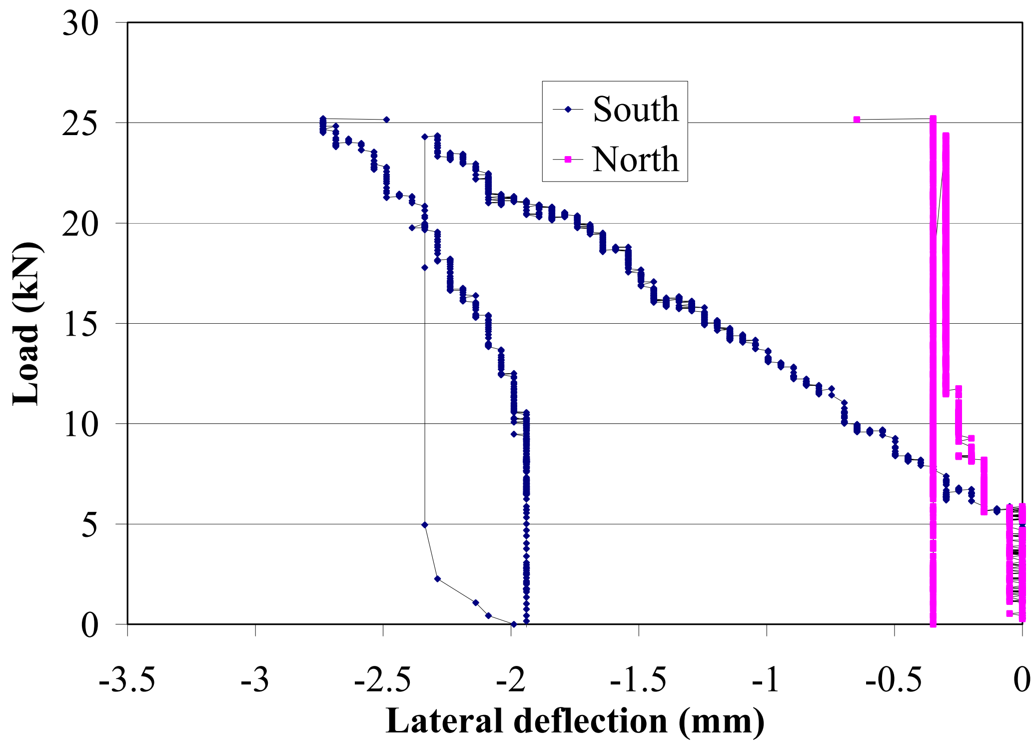


Figure 30 – Lateral deflections at the top of Wall 2 (clay plaster, bales on-edge).

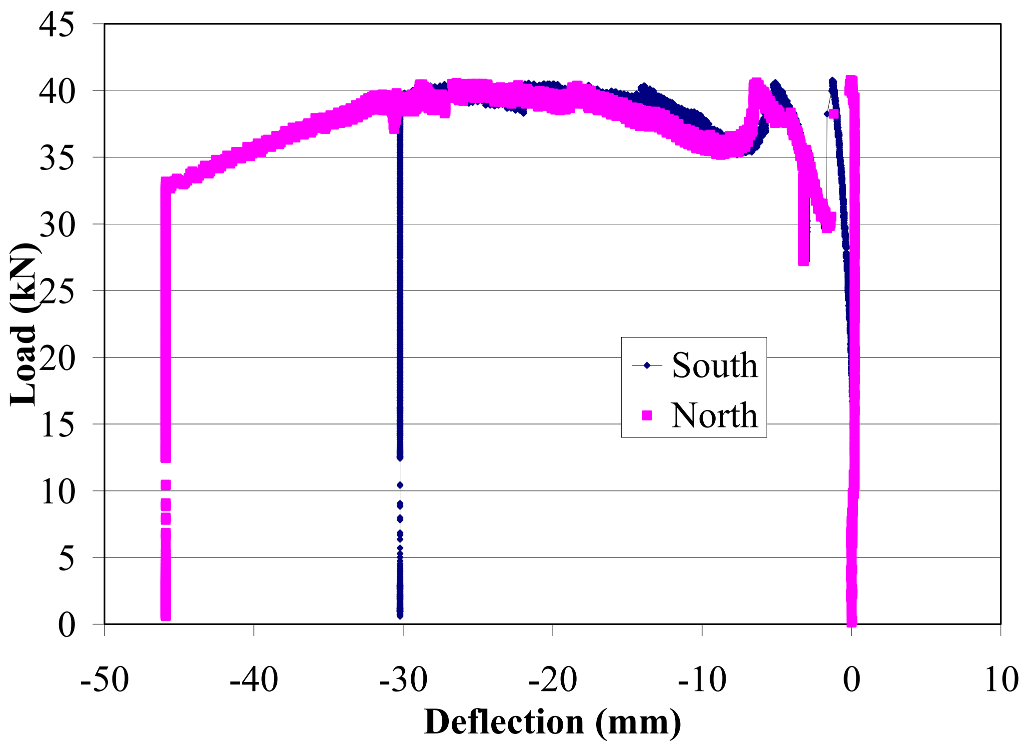


Figure 31 – Lateral deflections at the top of Wall 3 (clay/cement plaster, bales flat).

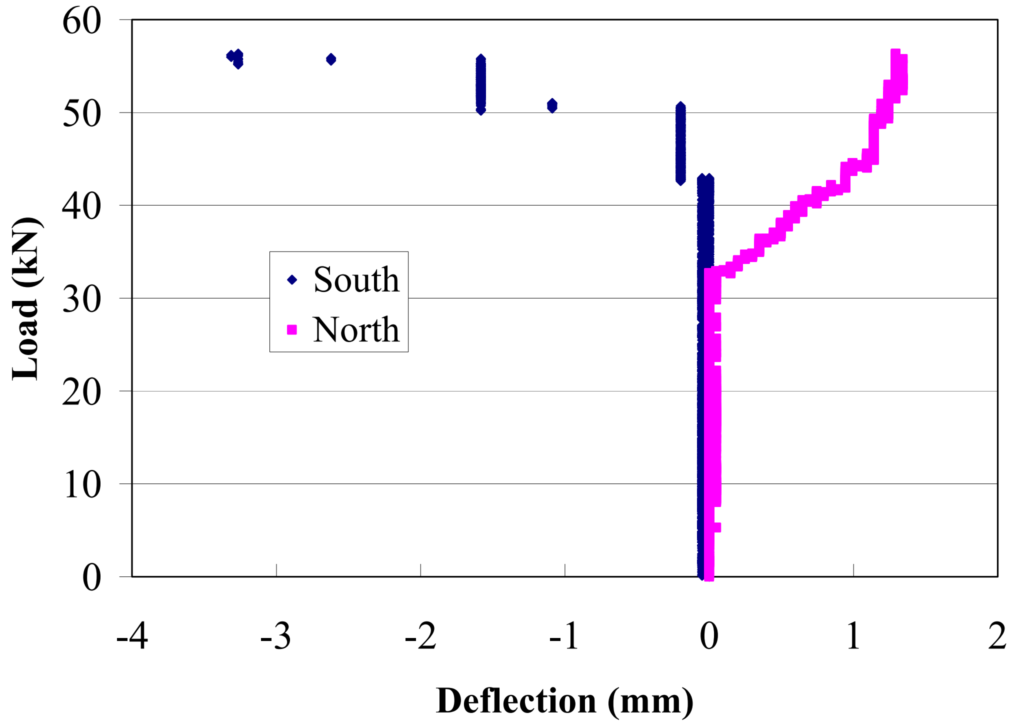


Figure 32 – Lateral deflections at the top of Wall 4 (clay plaster, bales flat).

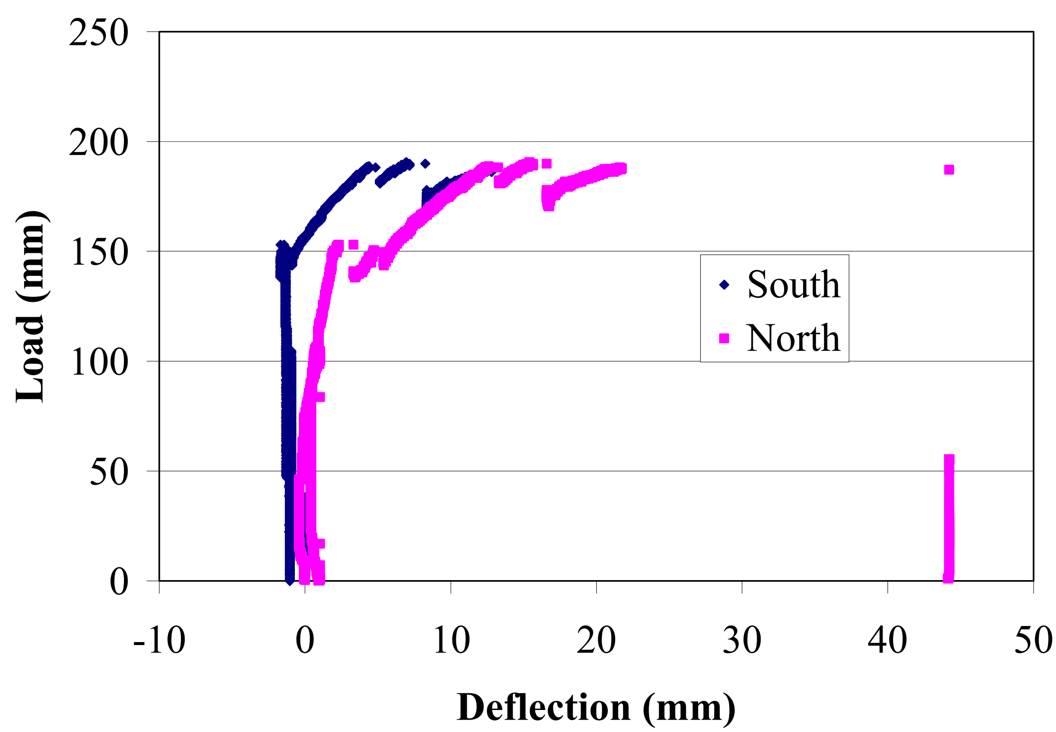


Figure 33 – Lateral deflections at the top of Wall 5 (cement plaster, bales flat).

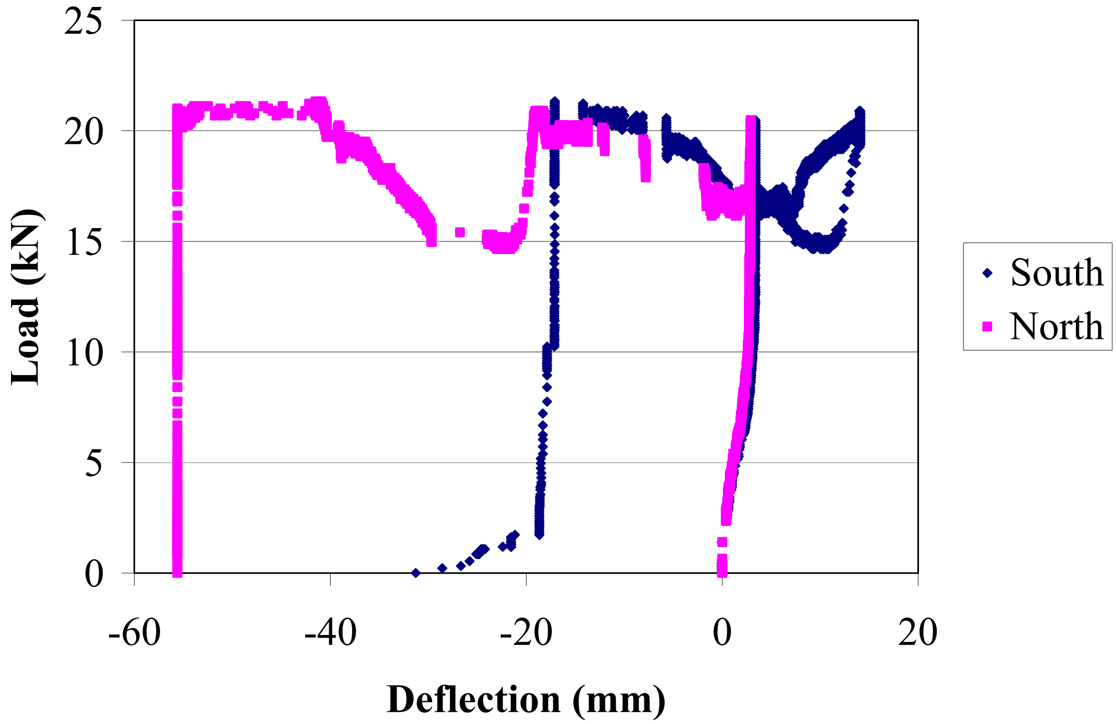


Figure 34 – Lateral deflections at the top of Wall 6 (clay plaster, bales on-edge).

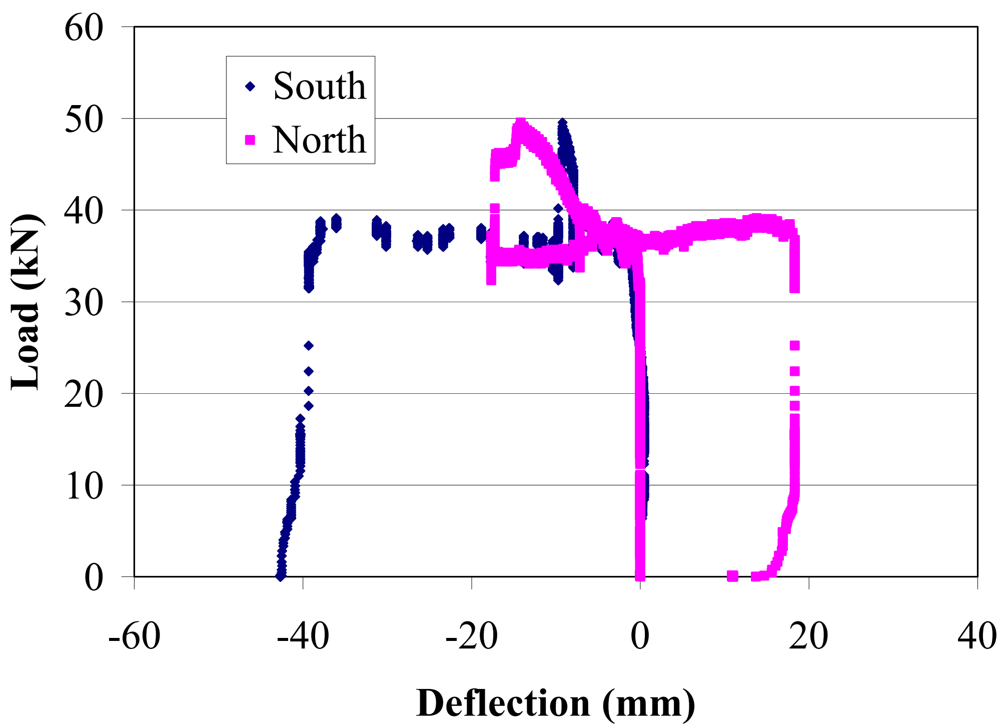


Figure 35 – Lateral deflections at the top of Wall 7 (clay plaster, bales on-edge).

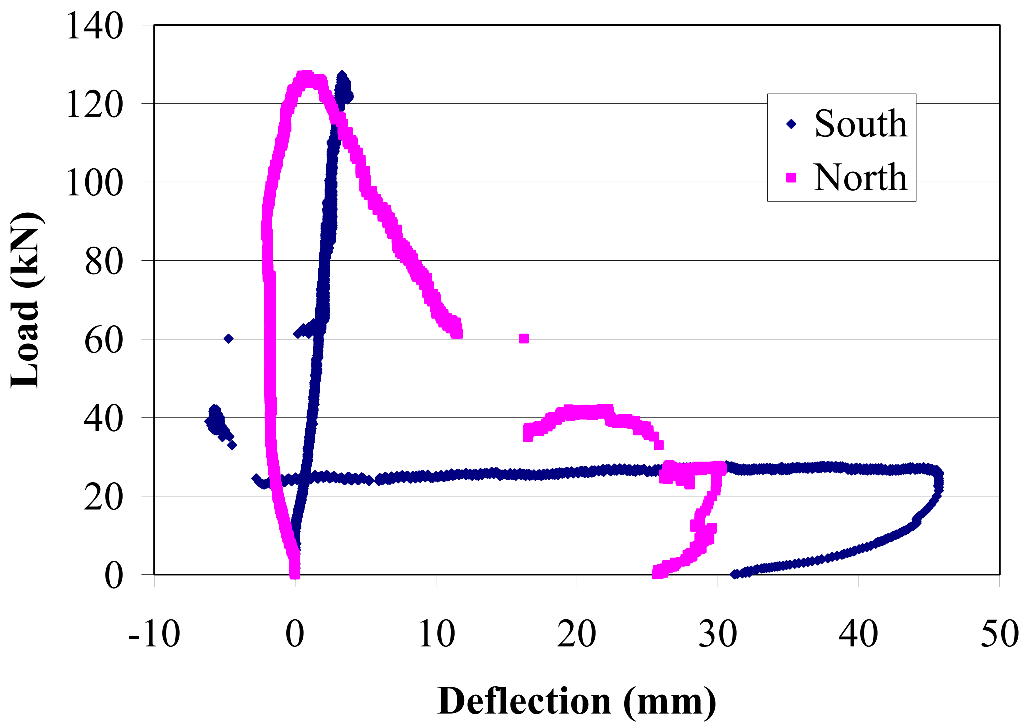


Figure 36 – Lateral deflections at the top of Wall 8 (cement plaster, bales on-edge).

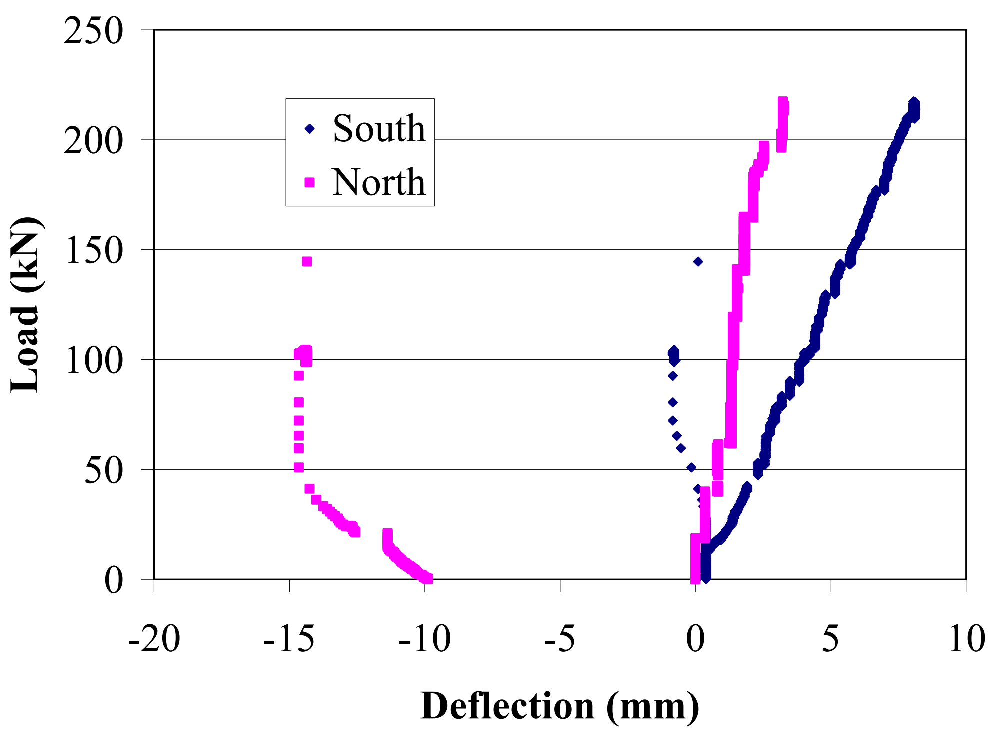


Figure 37 – Lateral deflections at the top of Wall 9 (cement plaster, bales flat).

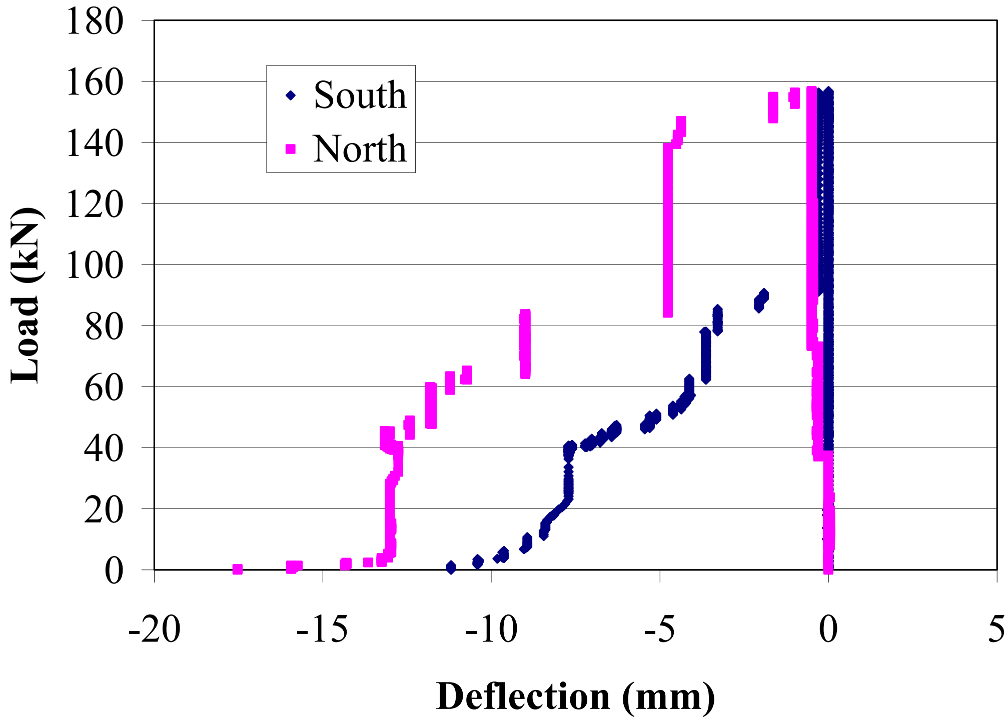


Figure 38 – Lateral deflections at the top of Wall 10 (cement plaster, bales flat).

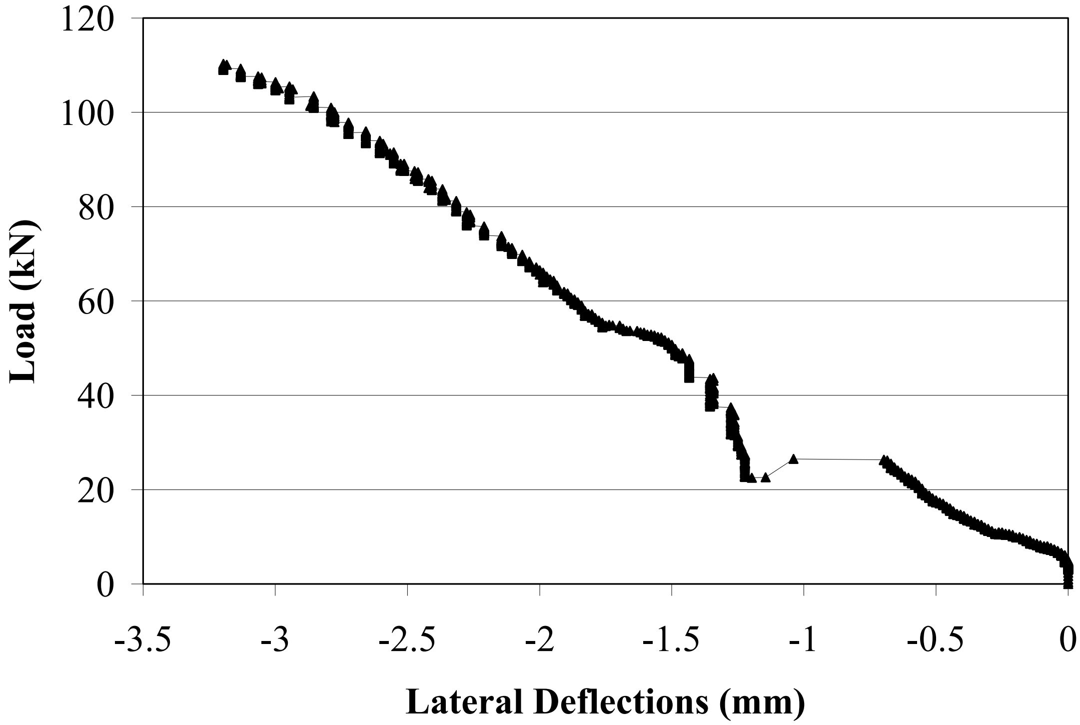


Figure 39 – Lateral deflections at the mid-height of Wall 1 (cement plaster, bales on-edge).

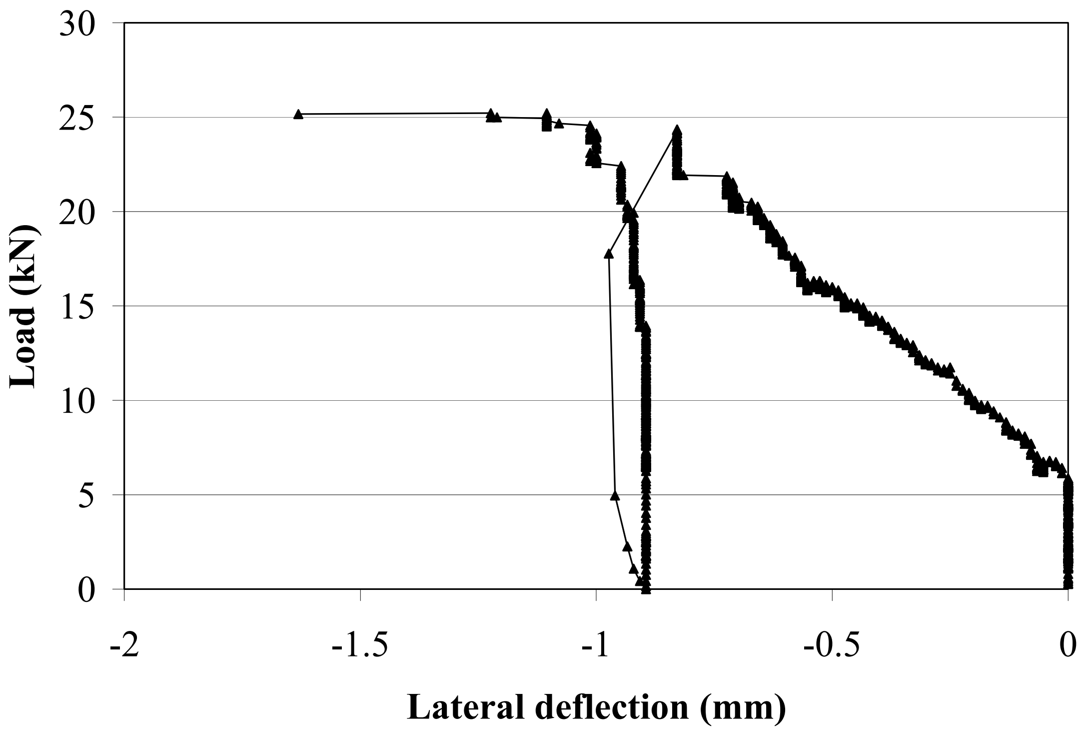


Figure 40 – Lateral deflections at the mid-height of Wall 2 (clay plaster, bales on-edge).

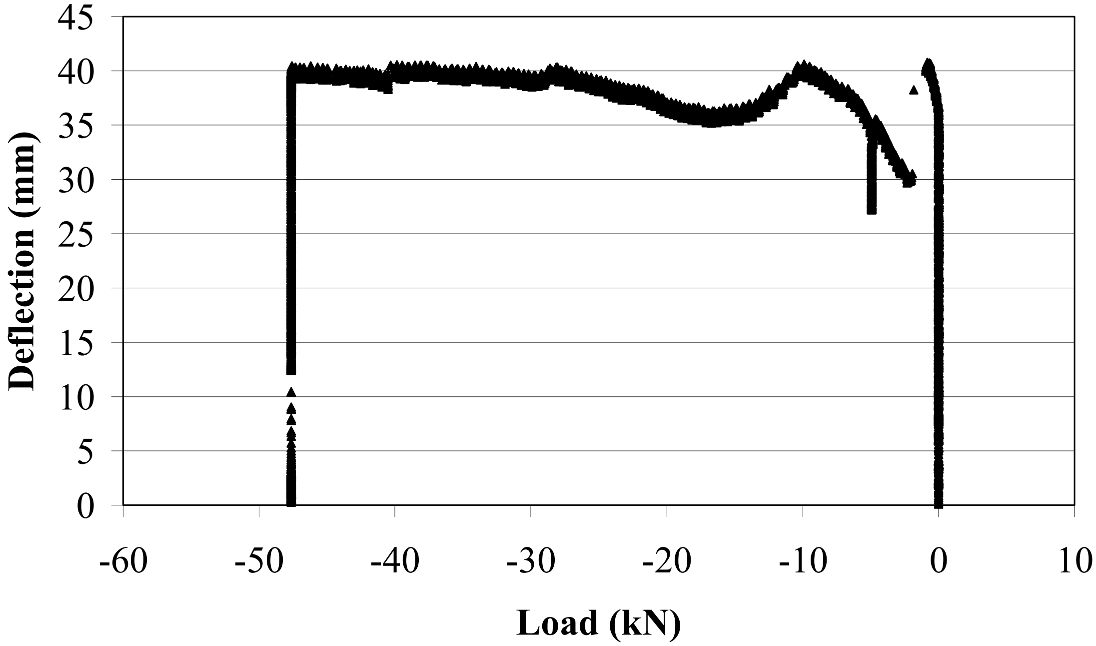


Figure 41 – Lateral deflections at the mid-height of Wall 3 (clay/cement plaster, bales flat).

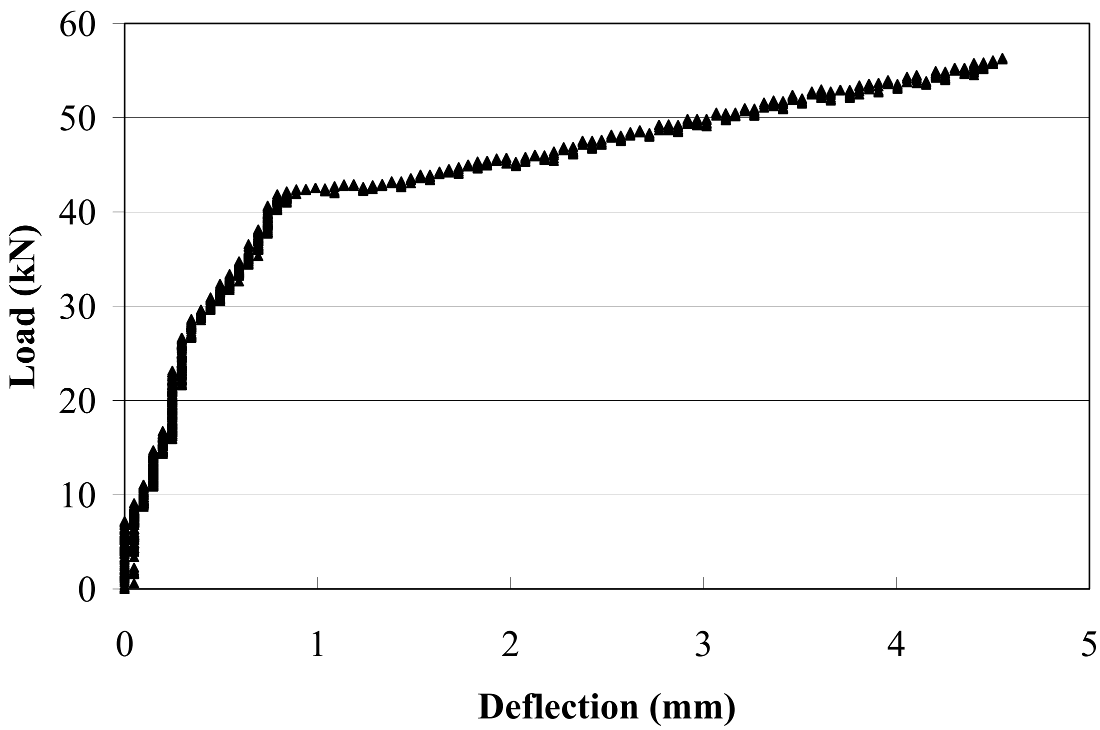


Figure 42 – Lateral deflections at the mid-height of Wall 4 (clay plaster, bales flat).

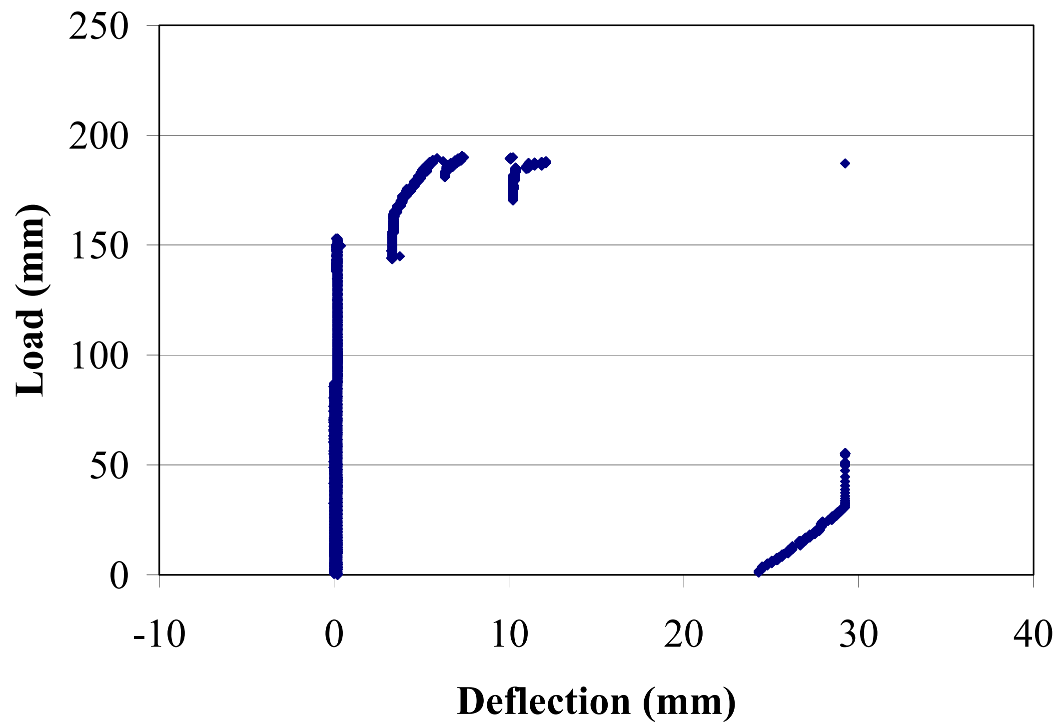


Figure 43 – Lateral deflections at the mid-height of Wall 5 (cement plaster, bales flat).

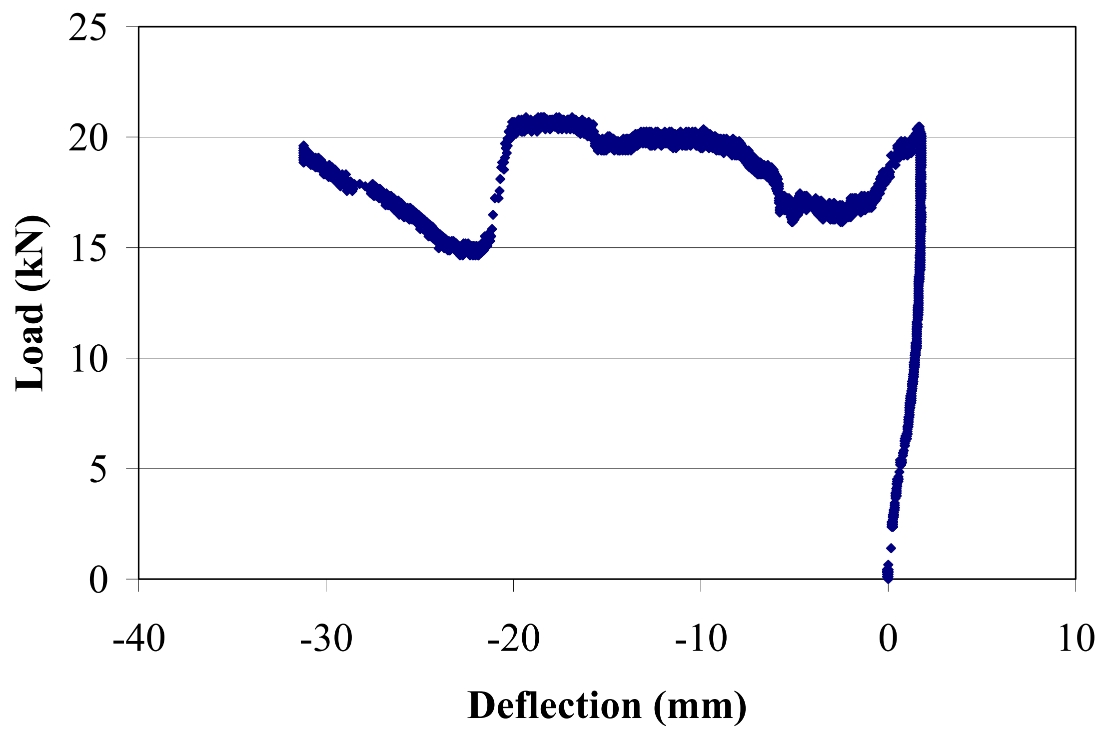


Figure 44 – Lateral deflections at the mid-height of Wall 6 (clay plaster, bales on-edge).

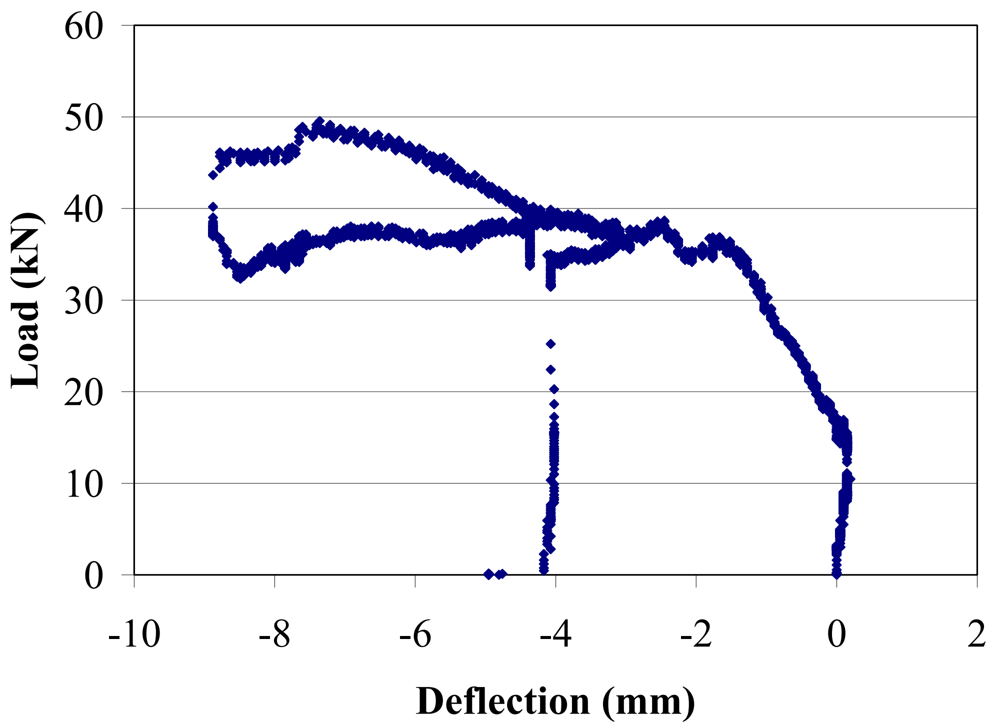


Figure 45 – Lateral deflections at the mid-height of Wall 7 (clay plaster, bales flat).

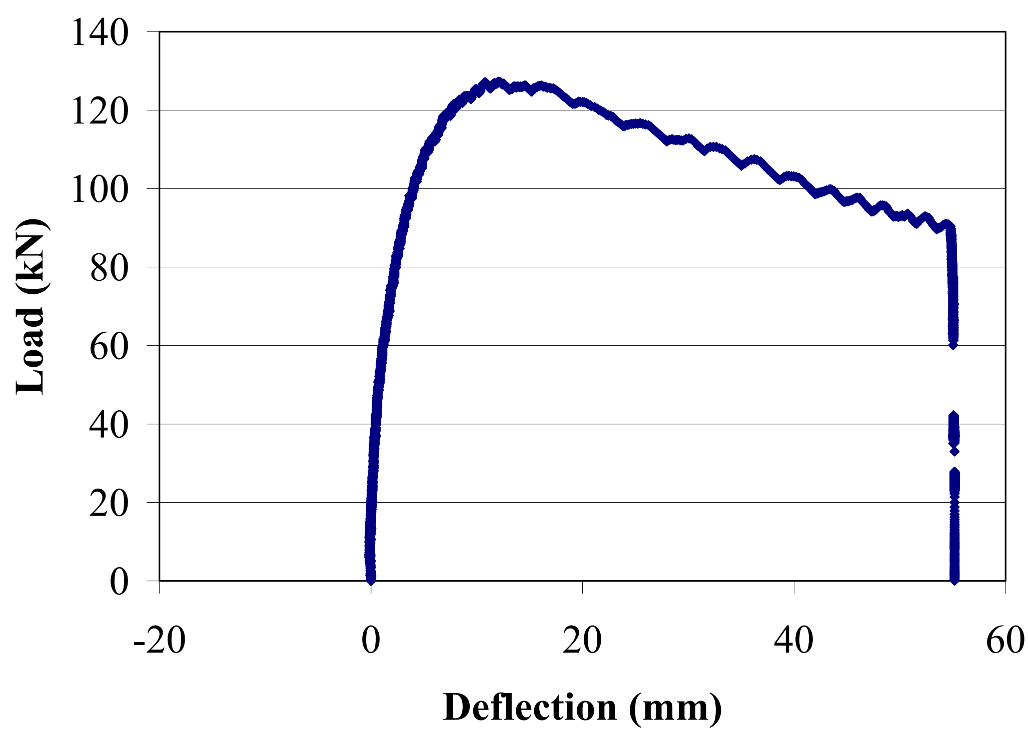


Figure 46 – Lateral deflections at the mid-height of Wall 8 (cement plaster, bales on-edge).

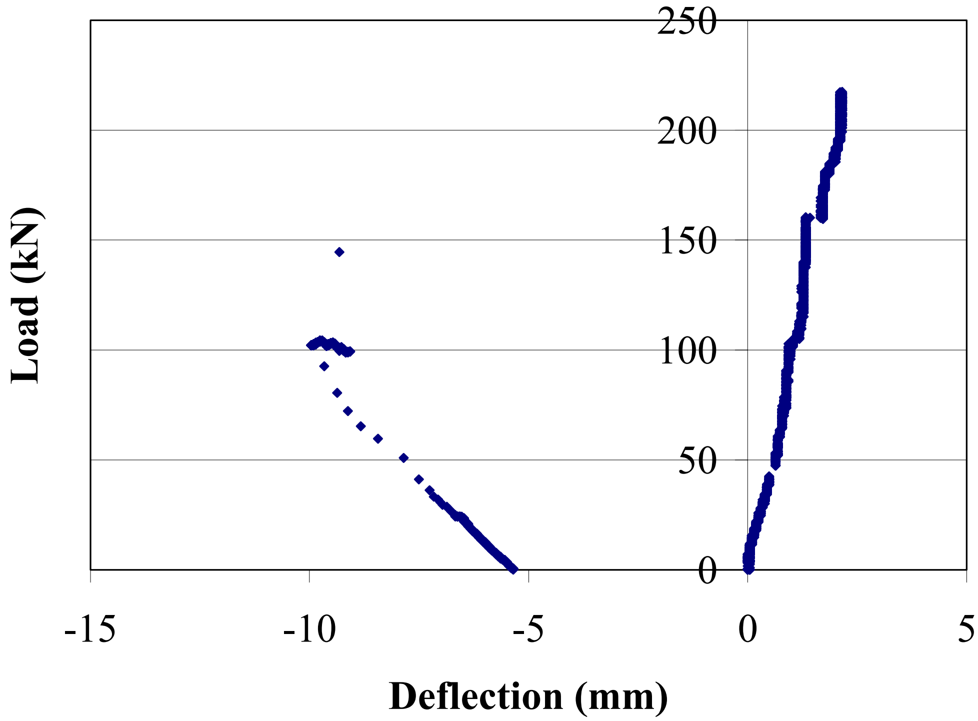


Figure 47 – Lateral deflections at the mid-height of Wall 9 (cement plaster, bales flat).

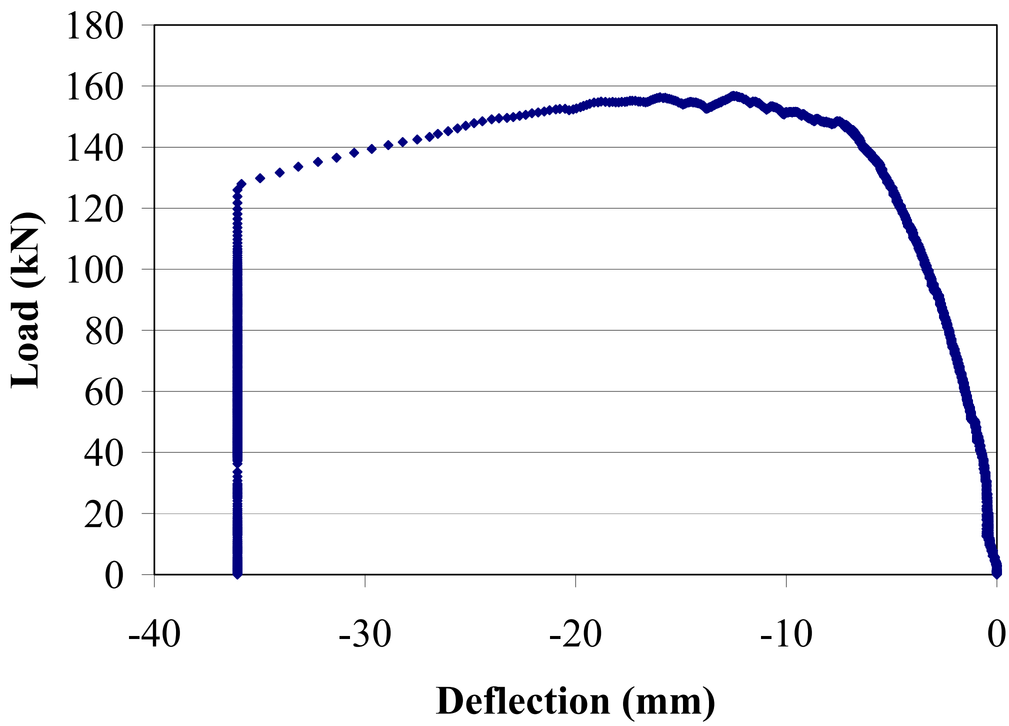


Figure 48 – Lateral deflections at the mid-height of Wall 10 (cement plaster, bales flat).

(a) (b)

Figure 49 – Failure of Wall 1 (cement plaster, bales on-edge): (a) Side view; (b) Isometric view.

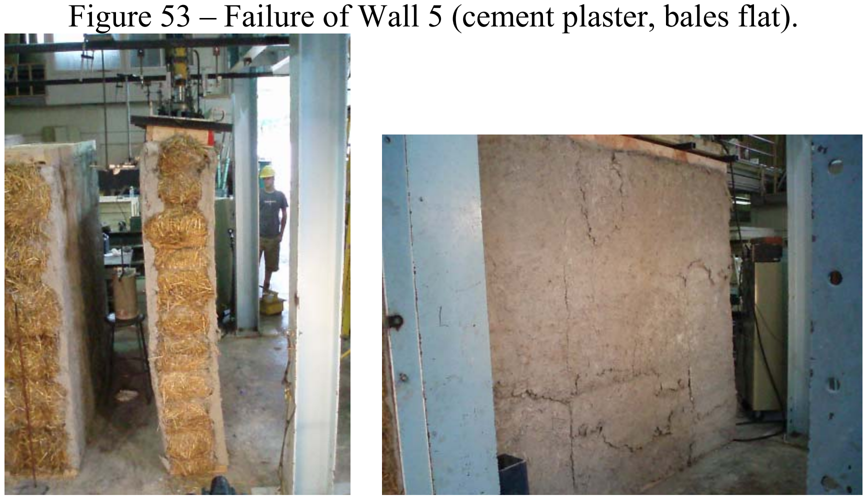
Figure 50 – Failure of Wall 2 (clay plaster, bales on-edge).

(a) (b)

Figure 51 – Failure of Wall 3 (clay/cement plaster, bales flat): (a) Side view; (b) Front view.

Figure 52 - Failure of Wall 4 (clay plaster, bales flat).

Figure 53 – Failure of Wall 5 (cement plaster, bales flat).



(a) (b)

Figure 54 – Failure of Wall 6 (clay plaster, bales on-edge): (a) Side view; (b) Isometric view.

Figure 55 – Failure of Wall 7 (clay plaster, bales flat).

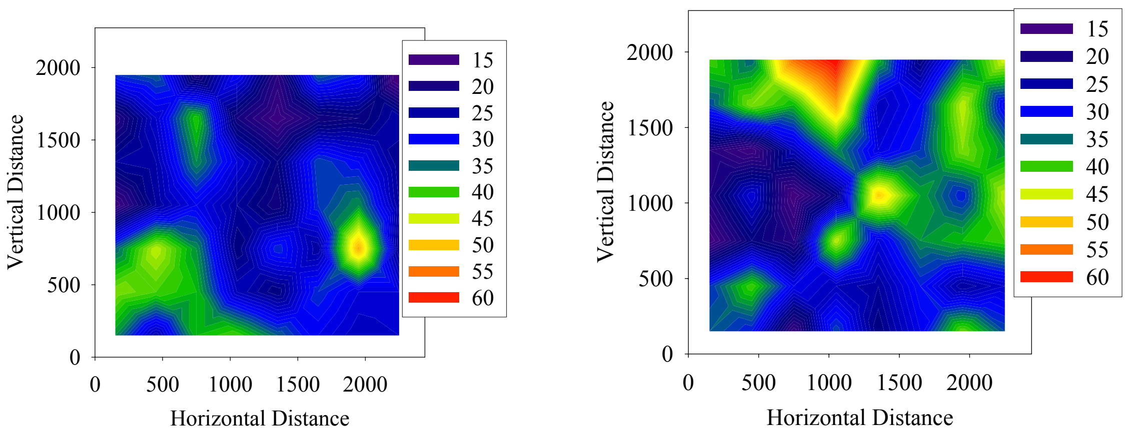
(a) (b)

Figure 56 – Failure of Wall 8 (cement plaster, bales on-edge): (a) Side view; (b) Close-up of cracking.

Figure 57 – Failure of Wall 9 (cement plaster, bales flat).

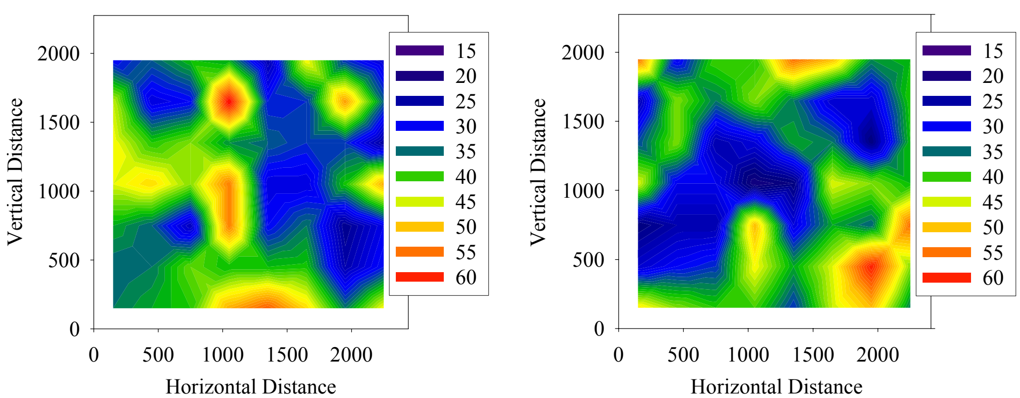
(a) (b)

Figure 58 – Failure of Wall 10 (cement plaster, bales flat): (a) Side view; (b) Isometric view.



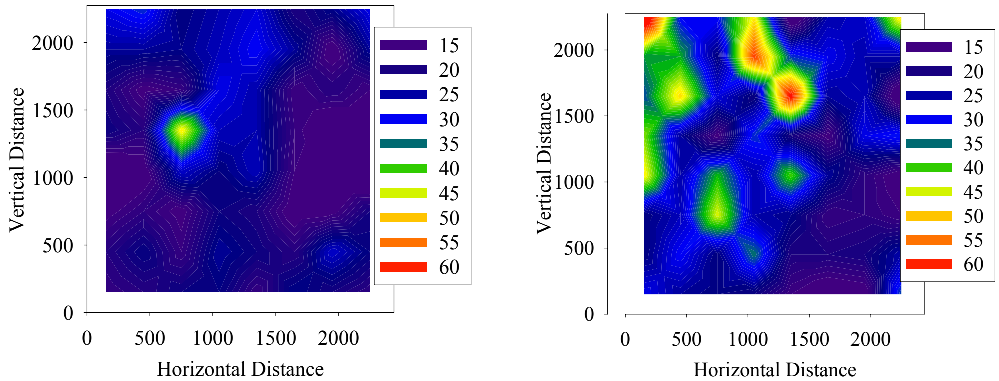
(a) (b)

Figure 59 – Contour plot of plaster thickness for Wall 6 (clay plaster, bales on-edge): (a) East side; (b) West side.



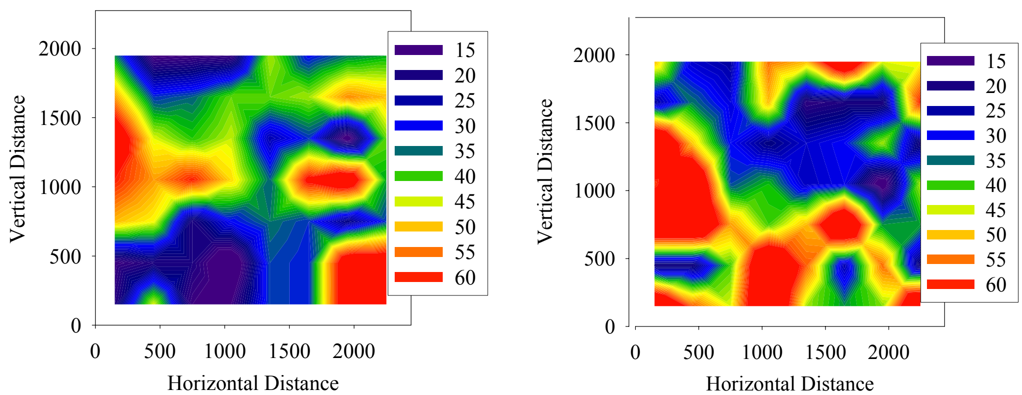
(a) (b)

Figure 60 – Contour plot of plaster thickness for Wall 7 (clay plaster, bales flat): (a) East side; (b) West side.



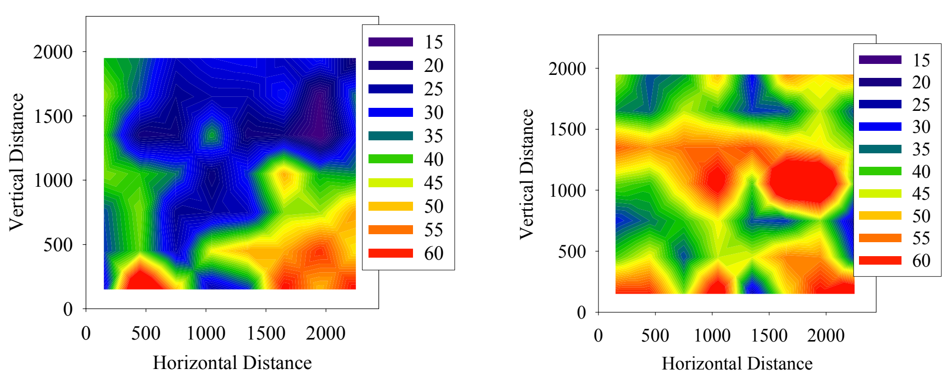
(a) (b)

Figure 61 – Contour plot of plaster thickness for Wall 8 (cement plaster, bales on-edge): (a) East side; (b) West side.



(a) (b)

Figure 62 – Contour plot of plaster thickness for Wall 9 (cement plaster, bales flat): (a) East side; (b) West side.



(a) (b)

Figure 63 – Contour plot of plaster thickness for Wall 10 (cement plaster, bales flat): (a) East side; (b) West side.

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