Problems in Rubble-Filled Random Masonry Walls

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Abstract

Old rubble-filled walls sometimes develop defects which appear as bows or bulges in one or both outer leaves. Common causes of such defects have been identified as rainwater penetration, repetitive cycles of freezing and thawing, and vibration from heavy traffic.

Sophisticated modern methods for identifying the nature of material within a wall have been investigated, and suggest that a technique using radar is likely to provide reliable results with minimal disruption or hazard to public health and safety.

Developments in repair techniques for infill material and outer leaves of rubble-filled walls have also been reviewed.

The paper will be interest to those with interests in the diagnosis and repair of defects in rubble-filled walls, particularly those of environmental or architectural importance.

Introduction

Many structures built in medieval times are still present today either as fully functional buildings or as ruins where all that remains are masonry elevations devoid of roof and internal floors. The walls of these structures have survived prolonged exposure to the elements and often a variety of loading conditions which were never envisaged at the time of their construction.

Random stonework with lime mortar was often used to construct these walls and considerable thicknesses were achieved (particularly in fortified buildings) by using random rubble as infill material between the inner and outer masonry leaves of the wall.

Structures constructed in this way that have survived to date range from buildings of major national and architectural importance (eg. Durham Cathedral) to buildings of smaller scale such as fortified farm cottages in more remote countryside locations. The age of these buildings makes them of historical interest and there is increasing pressure for such structures to be conserved and repaired in their original form. Engineers are often required to take a more sympathetic approach in methods of both investigation and repair of rubble-filled walls.

Analysis of the stability of random rubble-filled walls is made very difficult by the nature of their construction. To this end it is necessary to understand the methods of construction and the types of problems/failure encountered and to develop non-destructive methods of inspection to collect the information to allow more effective and sympathetic repairs to be carried out.

Methods of Construction

A common method of forming rubble-filled walls was to construct inner and outer leaves of stonework in which every stone was bedded in mortar in a similar manner to modern masonry practice. The cavity between the inner and outer leaves was then filled with random rubble as building progressed. Several variations can be found in this method of construction, possibly as a result of the wealth of the original owner of the building, the availability of skilled craftsmen or the quality of stone available locally.

Stone used for construction of rubble-filled walls can initially be considered as either "soft" or "hard". Soft stone (such as sandstone) was worked by hand with relative ease, allowing the simple production of regular right-angled shapes. This was historically known as "freestone" as it was "freely" worked. Hard stones had the benefit of greater durability but were more difficult to work by hand.

Construction of outer leaves of masonry may be regarded as either ashlar or rubble with numerous variations between these types. Ashlar is considered more formal construction comprising square or rectangular blocks of stone with "true" faces on at least five of six sides. Irregular jointing is, however, commonplace as it is unusual for all stones to be the same height or length.

The relative dimensions of individual stones seem to have been chosen so that the length of a stone on its bed did not exceed three times its height, and its depth into the wall was not less than half of its height.

These proportions have been found to vary depending on the type of stone.

Walls were also faced with squared rubble stones where individual stones have been worked to form true flat faces on four sides to give straight joints. These stones are laid in regular courses of even height, although the heights of adjacent courses may vary considerably. Squared rubble stones were also laid in courses as found in examples of "flat-bedded" and squared rubble walling.

Rubble walling in its most basic form is composed of both large and small irregular stones used indiscriminately either as delivered from the quarry or broken down by hammer to make them fit with one another. The faces of these stones were sometimes roughly worked or else not worked at all. This form of construction was most common in low-cost agricultural properties.

The thickness of the mortar beds in the outer leaves in all of the above masonry walls has been found to vary between 1 mm and 40 mm depending on the quality of the original construction. The common material originally used for bedding was generally a type of lime mortar. Mortar is particularly important in rubble construction as it prevents irregularities in the shapes of the stones from producing localised stress concentrations or "hard spots", leading to possible fracture of the wall when loaded.

Cavities between the inner and outer leaves of masonry have been observed to vary in width from as little as 150 mm to a maximum of 1000 mm. Considerable variation has been found in the material used for infill. The strongest form of infill was produced where the original masons filled the cavity with loose coursed rubble stones at the same time as the outer leaves were constructed. A semi-liquid sand:lime mortar was then poured over the loose stones of the infill to form a solid core. An example of this is shown in Figure 1. The weakest construction of rubble-filled walls has resulted where the cavity was simply filled with earth and relied upon the outer leaves of masonry for protection from the weather.

Figure 1: Rubble infill exposed

The most common form of material used to fill cavities in walls is random, irregular shaped and sized stones placed as construction progressed with apparently no attempt at consolidation (see Figure 2).

Very few of the walls investigated to date have any form of tie between the inner and outer leaves of masonry, which is contradictory to current practice in masonry design. In rare cases where ties were provided they took the form of long through-stones bonded into both inner and outer leaves at irregular and infrequent intervals. Such stones were considered objectionable as they would provide continuity of material, creating an uninterrupted path for moisture to pass to the interior face of the wall. The outer leaves appear to rely on restraint provided by occasional header stones projecting into the rubble core (see Figure 3).

Types of Problems and Failure

In common with other forms of construction, rubble-filled walls are susceptible to problems such as ground settlements, loss of lateral restraint etc.. In addition problems particular to rubble-filled walls arise from loss of integrity of the individual elements of masonry, in most cases producing bulges or bows in the wall in either a horizontal or vertical plane. Common causes are settlement or displacement of the rubble core particularly where this was not consolidated at the time of construction. Investigation of several structures has found that rubble material has been compressed at lower levels causing lateral pressure to be exerted on both inner and outer leaves of masonry.

Rubble in-fill material is very susceptible to damage from water penetration and frost action. Failure can occur where rainwater has been allowed to penetrate the inner material. The water inevitably percolates downwards, removing fine material and leading to consolidation at lower levels. Fill material can sometimes fall from its original upper position leaving large voids. Water in the core can also cause washing out of mortar from joints between facing stones, further weaken-

Figure 2: Irregular stones used for infill

Figure 3: Header stones provided for stability

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ing the wall. This in turn can lead to more water percolating the infill material. Serious and rapid deterioration is likely to occur if cracking has already taken place in the outer leaf of the wall, or if the top of the core material is exposed to the weather due to removal of a roof or coping stones.

Repetitive cycles of freezing and thawing of moisture within voids in the material leads to expansion in the size of the voids and increases the pressure on both inner and outer leaves of masonry. Freezing and thawing also breaks down stones within the inner core, producing further consolidation. In severe cases, loss of material from upper levels within a wall can create large voids, reducing the inner and outer leaves to independent structures.

Excessive weathering of the outer leaf of a rubble-filled wall can result in weakening or partial failure of localised areas of the face of the masonry. This is more serious than for solid masonry construction as internal pressure exerted on the outer leaf can displace stones in the weathered area. Once water has penetrated a wall subsequent loss of rubble infill from the affected areas can result in partial collapse.

Similar failures have occurred where modifications have been made to existing walls to provide openings in the walls without appropriate temporary works to stabilise the rubble core. The usual practice of providing "needles" to support the wall above an opening is unsatisfactory as rubble falls from the sides of the opening, leading to instability in the area adjacent to the new work.

Consolidation of rubble fill has also been observed where walls have been affected by the close proximity of road traffic, particularly that of heavy good vehicles. Ground-borne vibration from vehicles is transmitted to the rubble infill material and has a similar effect to water percolating through the core but without the additional problems of expansion and contraction produced by freezing and thawing.

Detrimental effects can sometimes occur when an existing rubble-filled wall is incorporated into a new development resulting in a change in loading within the existing wall. This can result in a greater eccentricity of loading due to greater width of wall. One structural failure has been investigated where residential accommodation had been built on top of a rubble-filled wall. The width of the modern construction was significantly less than that of

Figure 4: Bulging wall

the original wall. No attempt had been made to spread load across the full width of the old wall and loads from the new wall were transmitted directly into the outer leaf which subsequently failed in compression (see Figure 4).

Methods of Investigation

Most problems associated with rubble-filled walls develop over a considerable period of time. However, progressive deterioration of the rubble infill material can be accelerated if remedial work is not undertaken.

In the past structural problems in walls of this nature have tended to have been regarded as very serious, and symptoms have been treated rather than the underlying causes. This has often been due to difficulties in obtaining accurate information about the condition of the inner wall. Where doubts remained, the tendency has been to be over-cautious. Thus walls have been taken down and rebuilt, resulting in unnecessary expense and disruption and possibly conflicting with conservation requirements to retain the original structure.

Traditional methods of investigation have involved core samples taken from the wall to confirm the relative thicknesses of inner and outer leaves and the infill material. Sections of the inner or outer leaf were then available, inspection of the rubble material could be made. This only gave an indication of the condition of the wall in the area around the hole and may have temporarily weakened the wall.

It is now possible to use more scientific methods of investigation to inspect the nature and condition of material within a wall in a non-destructive manner and to gain more detailed knowledge, particularly over a larger area.

Techniques using X-rays and gamma radiation

X-rays can penetrate masonry to depths of approximately 500 mm; this range can be extended by using holes drilled into a wall. Legal requirements and concerns about health and safety aspects of using x-rays in public places, mean that local authorities must be informed, and the site must be cordoned off and warning signs displayed.

Radiography using gamma radiation is a specialised branch of photography and involves the exposure and processing of specially treated photographic film. It can successfully detect variations in features such as density of masonry.

Gamma rays can be expected to penetrate masonry to a maximum depth of about 0.6 m. Greater depths of penetration can be achieved using more powerful sources, but with more stringent but less convenient safety measures. Variations in density of material appear as gradations of

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grey in the radiograph and under- or over-exposure or incorrect development of a radiograph can produce confusing results.

Radiometry involves measuring the number of radioactive particles observed by a detector in a specified time and place. Material subject to test is placed between the radiation source and the detector and radiation passing through the specimen is measured. Alternatively, the radioactive source and a detector measuring back-scattered radiation can be combined into a probe unit which is gradually placed within or withdrawn from a pre-drilled hole. A method using back-scattered gamma radiation to examine the density of concrete within cast in-situ pile foundations was described by Preiss and Caiserman[1], and could be adapted for inspecting rubble-filled walls. The technique relies on the relationship between radiation count-rate and density of material through which the gamma waves are passing; background cosmic radiation must be measured so that its effect can be eliminated.

Scatter of results is likely as a result of the random nature of emitted radiation and non-uniformity of natural materials. The effect of natural scatter can be diminished by using moving the probe very slowly. A void or an inclusion of foreign matter generally produces a reduction in count rate, the magnitude of which is much greater than that produced by natural scatter.

Radar

Successful trials have recently been performed using a technique adapted from a system known as ground-penetrating radar used for remote sensing of sub-surface soil conditions. In its simplest form the system consists of a lightweight hand-held antenna and associated electronics for processing and recording data. Surveys are conducted by moving the antenna (which is connected by a cable to the electronic instrumentation) along a desired track. The antenna transmits pulses of electromagnetic radiation which are reflected from sub-surface features and discrete targets or individual objects. Reflected signals are transmitted through the cable for processing. A graphical display can be immediately produced from which sub-surface features can be identified.

The high speed of transmission, reflection and processing allows continuous profiles or cross-sectional views to be produced of the material below the surface or layers along the

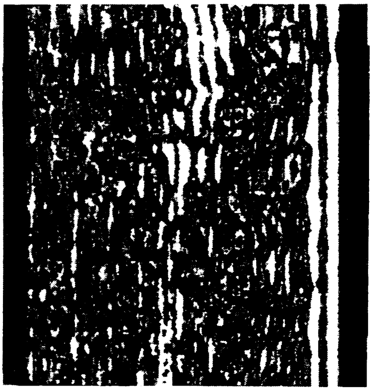
Figure 5: Radar image of rubble wall with internal voids

track of the antenna (see Figure 5).

The technique can be applied to rubble-filled masonry walls using signals with frequencies between 500-1000 MHz to achieve penetrations between 1-2 m with very high resolution. This enables the thicknesses of inner and outer leaves of masonry and the changes in width of the rubble fill, if any, to be determined.

This technique has been used successfully to investigate a rubble wall the front of which had been provided with a decorative brickwork skin during the early 18th Century. Several areas of wall were bulging and monitoring had shown that continuous and progressive movement was occurring. A search made using high frequency radar allowed details of the construction of the rubble-filled wall behind the facade to be determined. In addition, it was possible to differentiate between areas where bulges were caused by solely by detachment of the decorative brickwork and where there were more serious problems within the rubble wall itself. This enabled appropriate repairs to be undertaken without disruption of the elevation which was an important building in a highly sensitive conservation area.

Long-term monitoring

Useful information can sometimes be obtained by long-term monitoring of structural movements. Modern electronic equipment for measuring deflections can give very accurate values of three-dimensional movements at several points on a wall and allows accurate monitoring of settlement and lateral movement such as bulging or overturning of the wall. The equipment is that of a "total station" used for land surveying and which transmits an infra-red beam of light of specific wavelength at one or more reflective targets. Vertical and horizontal angles are measured by the station and distances are calculated by measuring the time taken for the infra-red signal to be returned. These values are then used by the station to calculate three-dimensional co-ordinates of a target point.

Accuracy to within 1 mm can be achieved if the distance from the instrument to the wall is kept to less than approximately 25 m. A major advantage of this system of monitoring is that the reflectors are small and unobtrusive and can be fixed and left in position during the monitoring exercise. Access to the target points is required for fixing the reflectors only during the initial visit; thereafter monitoring can be made by one person working at ground level with no further need of access to the targets.

Repair Techniques

The aim of remedial works performed on historic structures should be to undertake repairs in-situ with minimal disturbance and to leave no visible evidence of the works when complete.

Traditional methods of repairing rubble-filled walls have usually involved some form of rebuilding of either the entire wall or individual elements such as the outer leaves or rubble core.

Success in stabilising the walls has been achieved by applying grout to the core material without dismantling the masonry. A common method of grouting rubble walls is to use a grout composed of lime:PFA:Bentonite in a mix of 2:2:1. Alternatively a grout comprising low sulphate cement: lime:PFA mix in ratios of 1:2:1 can be used if more strength is required. The depth of wall to which grout is applied at any one time should be restricted to 1.0 m. This should be allowed to harden before further grout is added so as to prevent the build-up of pressure within the infill material.

The radar technique described above can be used to monitor changes in the density of the core material as a means of confirming satisfactory repair where grout has penetrated all the affected areas of the core.

Recent developments in chemical anchoring systems involving stainless steel rods fixed with epoxy resin can be used if a wall has deteriorated to such an extent that grouting alone cannot restore its structural integrity. These effectively tie the inner and outer leaves together, thereby stabilising the wall. When used in conjunction with grouting of a rubble-filled core this can produce the effect of a solid wall which is stronger and more tolerant to out-of-vertical alignment than the original wall. The spacing and diameters of the anchors can be varied to provide appropriate strength requirements. This method of repair allows a wall to be preserved without any apparent changes to its exterior or removal of internal finishes.

An alternative anchorage system consists of placing the stainless steel rods within fabric sleeves. A wall is drilled to allow anchors to be fixed into the inner and outer leaves of the masonry through the rubble core. Cementitious grout is then injected into the sleeve under low pressure. Flow is restricted by the flexible sleeve which expands and moulds itself into the shape of any voids and provides a positive bond with the stonework.

Closing Comments

Rubble-filled walls are a successful form of building as witnessed by their survival in some cases for hundreds of years after their initial construction. Their conservation is important and is highly dependent on a sympathetic approach from engineers charged with their repair. Application of modern codes of practice and methods of analysis can result in calculations which prove some walls to be unstable even though they have stood the test of time. This "historical" load test may be applied to walls in reasonable condition as an indication of their future stability.

Problems arise when there has been a failure in a wall; the onus is then to assess the need for structural repair in terms of present-day engineering and safety. This can often lead to replacement or reinforcement with steelwork or reinforced concrete. Development of a better understanding of the original philosophy of wall design and construction will help to combine engineering safety with the need for conservation. Use of improved modern non-destructive methods of investigation (such as radar) is likely to enable accurate identification and evaluation of real and potential problems, allowing appropriate repairs or preventative action to be taken.

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