Testing Fibre Stabilisation for Earthquake Resilience of Earth Mortar in Stone Masonry Construction


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ABSTRACT

Earth mortar stone masonry construction in seismically active zones present a risk to life. This paper documents a laboratory mortar test which demonstrates that fibre reinforcement of the mortar is likely to have some benefit in terms of the earthquake resilience of the masonry, by improving the structural integrity of the building and reducing the risk of total collapse during a seismic event. Further research is needed to quantify the required reinforcement density and to provide guidance on achieving the required density and distribution in practice.

Key words: Earthquake Resilience Earth mortar masonry

I. INTRODUCTION

Background

Stone masonry buildings with low strength mortar are particularly vulnerable to damage and collapse during seismic activity. This risk becomes more acute when unshaped stones are used and skilled craftsmen are not available. The Earthquake Engineering Research Institute (USA) identifies 'economic constraints and lack of proper training for local artisans' (Bothara & Brzev 2012, p15) as contributory factors to this vulnerability.

In response to the 2015 earthquake in Nepal, Arup engineers commented (Arup 2015 pers. comm. 15 December) on the challenges for rebuilding

'The most challenging places for rebuilding seem to be the remote and often impoverished areas where better materials are both too costly and difficult to transport to the sites. Here, various types of local stone and mud mortar (and sometimes timber) have been used for construction. In addition, there are many site related challenges: site amplification of ground motions, landslides, rock falls, irregularity in the structure created sloping sites and localized seasonal flooding.

As was demonstrated in the recent earthquake, stone masonry typically performs very poorly under earthquake loading and poses a significant risk to Life Safety. Ideally, we would avoid this type of system in high seismic hazard areas such as Nepal as even if the structure remains standing, dislodged bits of stone during the earthquake can still injure or kill the occupants.' (Arup 2015 pers. comm. 15 December)

Guidelines (for example: Arya, Boen, & Ishiyama, 2014; Bothara & Brzev 2012) and standards (for example: Government of Nepal 1994) offer a number of interventions which are able to increase seismic resistance of stone masonry construction, but this paper focuses on communities, unable to afford even modestly priced materials, and may not have access to stone masonry skills. It poses the question of whether vulnerability can be lessened for this group by addition of fibrous materials to earth mortar.

Strength of earth mortar can be increased by a process termed 'stabilising'. Additives such as 'ash, lime, cement, fibres, or cow dung' (Bothara & Brzev 2012, p49) are used in this way. Whilst these all increase strength of the mortar, this does not necessarily increase seismic resistance:

The use of cement or cement/lime mortar has been recommended by various codes and guidelines. A recent research study by Ali et al. (2010) has shown that use of cement mortar does not necessarily lead to improved seismic resistance of stone masonry buildings unless earthquake- resistant provisions are also incorporated (Bothara & Brzev 2012, p48)

No data was found on the seismic resistance behaviour of fibre stabilised earth mortar, therefore a series of laboratory tests were proposed to investigate this quality.

Fibres commonly used in earth mortar include straw, hay, hemp, sisal, and elephant grass (Bothara & Brzev 2012). This type of fibre was tested, along with man-made fibres which might commonly be available for low or no cost in a post disaster context: rope and tarpaulin.

Aim and Purpose

This paper presents the results of a series of tests undertaken on mortar samples. The aim of the research was to investigate the impact of various forms of reinforcement on the strength and integrity of mortar in traditional buildings (stone and mud mortar) and to present recommendations on how the mortar may be improved in practice.

Test samples were provided in grey cement mortar and traditional mud mortar with the following types of reinforcement:

- None (control)
- Rope
- Straw
- Shredded tarpaulin

The tests were performed by the Architectural Engineering Research Group, Oxford Brookes University UK under the supervision of Mr Ray Salter.

II. CORE OF THE DELIBERATION

Test apparatus and procedure

The aim of these tests was to determine the shear resistance of mortar samples with and without reinforcement. The tests were undertaken in the Lloyd compression testing machine on 350mm x 100mm x 25mm (approx.) samples supported on 100mm square steel blocks, such that the samples spanned approximately 150 mm between supports. The load was applied at a steady displacement rate at mid-span through a 100mm x 100mm steel bearing. The aim was to produce shear failure in the samples, although in practice failure was likely to be a combination of shear and bending (due to the geometry of the samples). The test set-up is shown in Figure 1.

- Two types of test were undertaken:
- Test to initial failure (drop in load)
- Test to total failure (sample breaks in two)

The aim of the first test was to determine the load and associated deflection at which the mortar failed in shear through cracking. This corresponds to the point at which the mortar joint may no longer be serviceable in the long term, but retains sufficient integrity to prevent collapse of the wall. During this test, the displacement of the bearing relative to the supports was increased at a steady rate (0.25 mm/min) until a reduction in load was observed. In the case of the unreinforced control samples, collapse of the test specimen occurred at this point.

Figure 1. Test set-up
Figure 1. Photograph of testing apparatus:
Source Oxford Brookes University Laboratory

The aim of the second test was to determine the degree of structural integrity provided by the reinforcement after the initial failure of the mortar. Following completion of the initial test, each sample was removed from the testing machine, inspected and photographed and then reinstalled into the machine. Load was applied for a second time until total failure was observed, at which point the load reduced rapidly to zero and the sample broke into two pieces. In some cases, where the quantity of fibres was sufficient to prevent separation of the two halves of the sample, the test was terminated at a maximum displacement of 10 mm.

Note:

The following notation is used in the test references:

C = control (no reinforcement)

R = rope

S = straw

T = tarpaulin

Test results and analysis

Prior to testing, the samples were inspected for damage and photographed. The initial condition of the test specimens is shown in Figure 2.

Figure 2. Photograph of Initial condition of samples prior to testing. Source Oxford Brookes University Laboratory

It is apparent that the earth mortar specimens were in noticeably worse condition than the normal mortar.

The results of the initial shear tests are presented in Table 1.

Table 1. Initial shear tests Source Oxford Brookes University Laboratory Mortar test report (Heywood 2015)

Test reference	Maximum force (N)	Movement at max force (mm)	Shear stress (N/mm^2)[1]	Comment
C1/grey	-	-	-	Already failed
C2/grey	-	-	-	Failed during set-up
C3/grey	134	0.46	0.050	Broke in two pieces
R1/grey	103	0.18	0.039	Fibres still holding
R2/grey	97	0.17	0.036	Hairline crack only
R3/grey	141	0.38	0.056	Cracked but still one piece
S1/grey	110	0.44	0.043	Hairline crack only
S2/grey	114	0.31	0.044	Hairline crack only
S3/grey	100	0.30	0.037	Hairline crack only
T1/grey	103	0.25	0.039	Cracked but still one piece
T2/grey	138	0.61	0.053	Broke in two – few fibres
T3/grey	252	2.55	0.097	No reduction in force[2]
C1/red	-	-	-	Already failed
C2/red	176	0.50	0.064	Broke in two pieces
C3/red	-	-	-	Failed during set-up
R1/red	107	0.65	0.038	Cracked but still one piece
R2/red	221	0.72	0.073	Cracked but still one piece
R3/red	-	-	-	Already cracked through
S1/red	114	0.47	0.040	Hairline crack only
S2/red	100	0.79	0.036	Load increased to plateau
S3/red	114	0.32	0.041	Hairline crack only

T1/red	121	1.52	0.044	No reduction in force[3]
T2/red	-	-	-	Already cracked through
T3/red	-	-	-	Already cracked through

Notes:

1. The shear stress value was obtained by dividing the maximum force by the measured cross-sectional area.
2. Test T3/grey was loaded to the maximum applied force of 200N (plus bearing weight of 52N) with no reduction in load or sign of failure. It was only apparent that a crack had occurred on removal of the specimen from the testing machine.
3. Test T1/red was loaded to the maximum displacement of 1mm with no reduction in force. The test was then repeated towards a 2mm maximum displacement, but was stopped once a crack was spotted.

In most cases, initial failure resulted in a crack through the depth of the sample, leaving the two halves of the sample held together only by the fibres and hinged in the middle. In some cases, however, the crack was only hairline in nature and the test sample remained intact as a single unit. Test samples with sparse fibres were no better than the unreinforced controls and broke in two. With the exception of T3/grey and R2/red, there was little apparent improvement in shear strength due to the inclusion of the fibres. It was, however, apparent that the fibres provided a significant degree of resilience that allowed some samples to remain intact after initial failure.

In order to determine the ultimate failure resistance of those samples that had not already been broken in two, they were reinstalled in the testing apparatus and loaded to collapse. The results of these tests are presented in Table 2.

Table 2. Ultimate failure tests Source Oxford Brookes University Laboratory Mortar test report (Heywood 2015)

Test reference	Maximum force (N)	Movement at max force (mm)	Maximum movement (mm)	Comment
R1/grey	389	8.97	10.00[1]	Some fibres still attached
R2/grey	465	6.10	10.00[1]	Many fibres in centre
R3/grey	131	3.90	6.00	
S1/grey	148	4.63	7.30	
S2/grey	310	1.43	5.35	
S3/grey	234	3.87	7.62	
T1/grey	131	3.42	7.57	
T3/grey	296	3.57	10.00[1]	Many fibres in centre
R1/red	352	11.42	11.42[2]	Loaded twice but no failure
R2/red	445	7.07	10.00[1]	
R3/red	221	7.73	10.00[1]	
S1/red	186	2.89	6.67	
S2/red	141	1.49	5.08	
S3/red	183	2.80	9.10	
T1/red	269	9.36	10.00[1]	Many fibres in centre
T2/red	110	1.82	4.80	Some fibres still attached
T3/red	79	2.14	2.45	Some fibres still attached

Notes:

1. Test stopped automatically at 10mm without failure of the sample.
2. Test stopped automatically at 10mm without failure of the sample. Test then resumed and sample loaded to a maximum applied force of 300N (plus bearing weight of 52N) with no reduction in load or sign of ultimate failure.

In most of the cases, the load increased to a maximum before falling to zero, at which point the remaining fibres either failed in tension or pulled out of the mortar. In a few cases, however, the test was stopped automatically at a pre-set displacement limit of 10mm before the load had reached zero. In one case, the load continued to increase until the test was stopped automatically at an applied force of 300N (plus the bearing weight of 52N). It was noted that the key factor that determined whether the samples broke in two or remained intact to 10mm displacement was the density of fibres in the central region of the sample. Samples with sparse fibres or those with fibres only on the top or bottom surface of the sample did not perform as well as those with many fibres located at mid-depth. The type of reinforcement and even the type of mortar had little impact on the performance of the samples.

After completion of the test programme, the samples were photographed for a second time. The final condition of the test specimens is shown in Figure 3.

Figure 3. Photograph of final condition of test samples Source Oxford Brookes University Laboratory

III. CONCLUSIONS and RECOMMENDATIONS

A programme of shear tests has been undertaken on mortar samples with and without reinforcement. Significant variability in the initial resistance (when the samples first cracked) and ultimate failure was observed, but there was no clear distinction between the three types of reinforcement and two types of mortar. The performance of the samples between initial cracking and ultimate failure was largely dependent on the density of the reinforcement fibres and their location rather than the type of fibre or mortar. Samples with sparse fibres or those with fibres only on the top or bottom surface of the sample did not perform as well as those with many fibres located at mid-depth.

Although the reinforcement did little to improve the shear resistance of the mortar, the improved post-cracking behaviour is likely to have some benefit in terms of the earthquake resilience of the masonry, by improving the structural integrity of the building and reducing the risk of total collapse during a seismic event. Further research is needed to quantify the required reinforcement density and to provide guidance on achieving the required density and distribution in practice. Any further testing should be undertaken on cylinder samples and ultimately on small masonry panels subjected to dynamic loading.

The ultimate aim for this programme of testing is to promote safer construction to reduce risk of injury, death, and loss of property, using locally available and sustainable skills and materials. Field testing and expert advice as well as local knowledge and partnerships with non-governmental organisations working in the area would be invaluable in this respect. This paper therefore proposes further testing in the laboratory and in the field to fully investigate the behaviour of reinforced earth mortar samples including the efficacy of varying lengths and densities of fibre, It is also recommended laboratory testing be carries out on sample wall panels to determine the effect of reinforced earth mortar on the appropriate construction under seismic simulation.

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