Improving the shear resistance of adobe masonry for rebuilding and new construction purposes

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Abstract

Adobe is a common building material used all over the world, especially in low cost housing. The areas in which this material is utilised also happen to be regions prone to experiencing earthquakes. Adobe masonry has a comparatively low shear resistance and fails, due to its brittle limitations resulting in virtually no ductile capability. It is therefore very susceptible to earthquake-induced loads.

The present studies focus on the improvement of the shear resistance of adobe masonry by adding reinforcements in form of natural fibres to the clay bricks and enhancing the bond between mortar and stone by optimizing the surface of the clay bricks and mixing additives to the clay mortar. Furthermore, the fibre reinforcement should enhance the energy absorption capacity of the clay and therewith the ductility and earthquake resistance of the masonry.

Keywords: adobe masonry, historical masonry buildings, earthquake, energy absorption, fibre reinforcement, clay, Arg-e Bam.

1 The historical citadel of Arg-e Bam

Built before 500 BC and used until 1850 AD, the ancient citadel of Arg-é Bam (Iran) was the largest adobe building in the world. On December 26, 2003 a major earthquake struck Bam and the surrounding Kerman province with a magnitude of 6.3 on the Richter scale. The earthquake destroyed about 70 percent of the buildings in Bam city and more than 80 percent of the historical Citadel itself.

Bam and its cultural landscape were inscribed on UNESCO's World Heritage List and on the World Heritage List in Danger in June 2004.

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Figure 1: The historical Citadel in Bam before and after destruction.

A team from the Faculty of Architecture at the TU Dresden, under the direction of Prof. Jäger, has been participating in several projects in close collaboration with the Recovery Project team from ICHHTO concerning the restoration of the Citadel since 2006.

2 Shear resistance of masonry

Buildings under seismic loads are mainly exposed to horizontal forces, which have to be primarily transferred as shear stress by walls, loaded as diaphragms. These shear loads have to be superposed with vertical forces resulting from permanent loads of the structure as well as from the live loads. The behaviour of masonry walls subjected to shear and compression forces has been described by the failure theory of Mann/Müller [1], also forming the base for the shear verification according to the German masonry code DIN 1053 [2]. This theory distinguishes four failure criteria for masonry; gaping of the units, friction failure of the horizontal joint, tension failure of the bricks and crashing of the masonry (see Figure 2).

In short, it can be assumed, that this theory is also valid for adobe-masonry under shear loads. The typical damage modes of the mentioned failure criteria can also be found on the adobe-walls inside the historical Citadel in Bam which were destroyed by shear forces resulting from the earthquake in 2003.

According to the theory of Mann/Müller [1], the shear resistance of masonry walls depend from the following material properties:

- Compression strength of the masonry
- Tensile strength of the bricks
- Initial shear strength and friction coefficient mortar-brick
- Adhesive tensile strength mortar-brick

The subsequent tests (herein described) were orientated to improve the shear strength and with it the earthquake resistance of adobe masonry. Therefore it was intended to increase the tensile strength of the bricks and in this way the compression strength of the masonry by adding fibre reinforcement to the clay bricks. Furthermore, additives to the clay mortar and the optimization of the brick-surface should additionally improve the bond between mortar and brick.

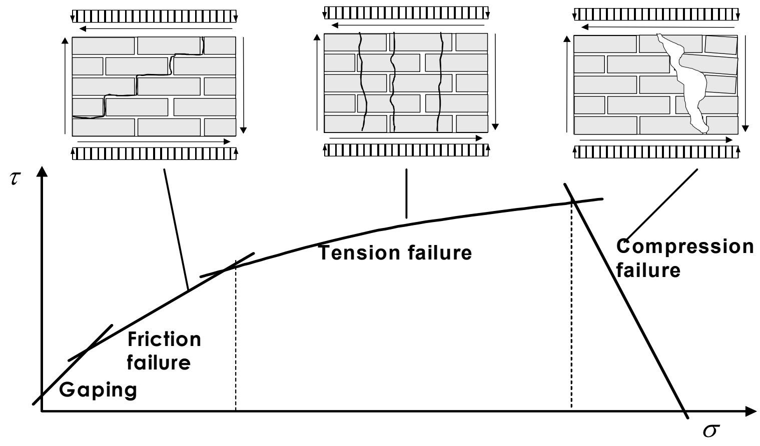

Figure 2: Failure criteria for masonry subjected to shear loads according to Mann/Müller [1].

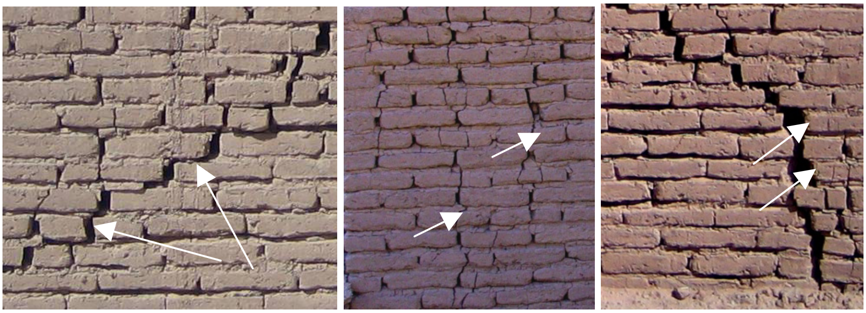

Figure 3: Friction (left), tension (middle) and beginning of shear-compression failure (right, crashing) of the adobe-masonry.

3 Fibre reinforced adobe-bricks

The traditional adobe construction uses clay as a natural, easy reusable and local available material which incurs low costs. It was therefore decided to add exclusively natural fibres as reinforcement to the row brick material in order to complement the tradition, as well as to meet the requirements of the common charters and guidelines for restoration and conservation of architectural heritage buildings in case of the world heritage site of Bam.

Initial tests have been executed with Sisal-, Flax-, Hemp-, Coconut- and Coco-palm fibres. Following the first expedition to Bam, the fibre of the Date palm (Phoenix dactylifera) which is widely available in the region due to the date production and traditionally used for the fabrication of ropes, was included in the research program. To investigate the suitability of the different natural fibres, tension and compression tests were carried out on the fibre reinforced clay bricks. The maximum strength of the various bricks was measured as well as the energy absorbed by the test specimen until the point of failure. This can be assessed as criteria for the energy dissipation capacity in case of earthquake actions.

While the test specimens without reinforcement show a sudden, brittle collapse, the fibre reinforcement of the bricks can continue to absorb tension load even after the failure of the clay itself (see Figure 4).

Figure 4: Failure process of reinforced clay bricks under tension.

It was found out that the unreinforced clay and the industrial produced bricks achieve the highest tensile strength, due to the undisturbed clay matrix, but have virtually no post-peak behaviour. The fibre reinforcement, however, reduces the content of clay in the test specimens and influences the inner cohesion of the row clay material negatively what results in a decrease of the tensile strength. As visible in Stress-Deformation-curve in Figure 5, the Sisal fibre achieves the best post-break results in terms of fibre-absorbed-tension, maximum deformation and energy absorption, whereas the performance of the Date palm fibre, favoured for the application in Bam, is considerably lower (see Figure 8).

Under compression the cross-section area of the unreinforced test specimens is reduced by cracks resulting from transverse tension, causing a brittle failure. In reinforced clay bricks cracks also occur due to transverse tension, but do not cause a reduction of the compression absorbing cross-section area, because the debris continues to be held in place by the fibres. Therefore the specimens maintain their shape during the test and display a ductile failure.

Similar to the tension tests, the unreinforced test specimens achieve a higher compressive strength than the bricks with fibre reinforcement. However, the strength degradation in the post break process is more significant and the failure is less ductile. Again the Sisal fibres attain the best results with a comparatively low decrease of the maximum compressive strength and a high energy absorption.

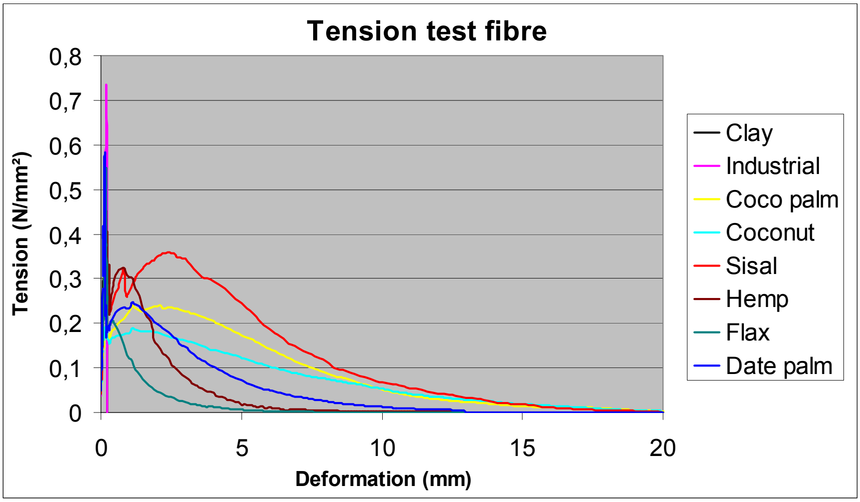

Figure 5: Stress-deformation curves of fibre reinforced clay under tension.

Figure 6: Failure process of unreinforced and reinforced clay bricks under compression.

As indicated by the displayed Stress-Deformation curves, the application of natural fibres as a reinforcement of clay bricks causes a marginal reduction of the tensile and compressive strength, but significantly increases the capacity to absorb energy. From the selection of tested fibres, Sisal was determined as the best suitable natural fibre, whilst the application of locally sourced Date-palm fibres also demonstrated a considerable enhancement of the energy absorption.

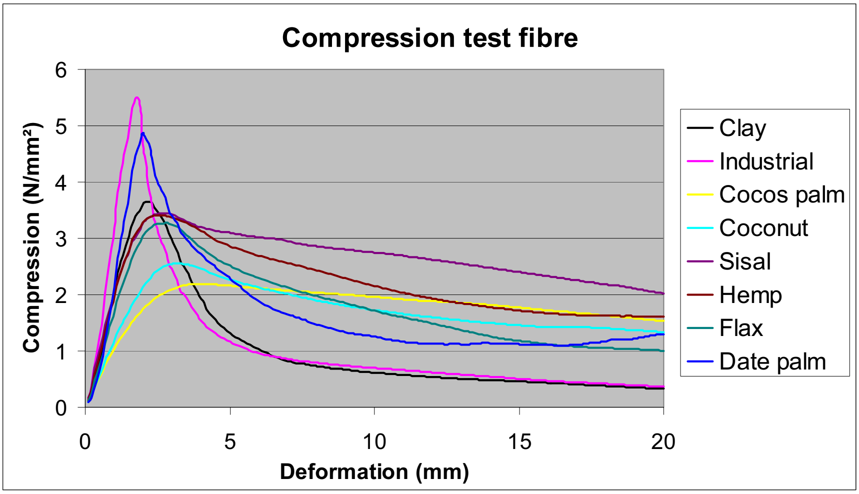

Figure 7: Stress-deformation curves of fibre reinforced clay under compression.

Fibre	Tension				Compression			
	Tensile strength		Energy absorption		Compressive strength		Energy absorption	
	N/mm²	%	Nmm/mm²	%	N/mm²	%	Nmm/mm²	%
Clay	0,668	85,62	0,06420	2,93	3,7313	65,32	20,0702	38,52
Industriell	0,780	100,00	0,07625	3,48	5,7125	100,00	22,0627	42,34
Cocos palm	0,233	29,86	1,76744	80,63	2,2056	38,61	36,0978	69,28
Coconut	0,213	27,29	1,43011	65,24	2,5621	44,85	34,2444	65,73
Sisal	0,508	65,05	2,19206	100,00	3,4828	60,97	52,1024	100,00
Hemp	0,643	82,36	0,86360	39,40	3,4565	60,51	43,4880	83,47
Flax	0,630	80,78	0,34017	15,52	3,3394	58,46	35,0070	67,19
Date palm	0,690	88,37	1,05470	48,11	5,0562	88,51	33,7245	64,73

Figure 8: Tensile/compressive strength and energy absorption of fibre reinforced clay under tension/compression.

3.1 Analysis of fibres

The differences in the performance of the various fibres could result either from inherent variable tensile strength of the fibres or from different bonding conditions between fibre and surrounding clay. The tensile strength has been determined for Sisal and Date-palm fibres. While the Sisal fibres proved to be very homogenous with diameters ranging from 0.18 and 0.22 mm, the thickness of the Date-palm fibres varies considerably. Consequently, the Date-palm fibres were subdivided for the test into fine (0,15-0,30 mm) middle (0,31-0,60 mm) and coarse (0,61-0,90 mm) fibre categories.

The average tensile strengths for the fibres determined by tests are:

Sisal fibre	840,09 N/mm²
Date palm fibre – fine	164,15 N/mm²
Date palm fibre – middle	139,87 N/mm²
Date palm fibre – coarse	115,27 N/mm².

Figure 9: Sisal fibres (left) as well as fine, middle and coarse Date palm fibres.

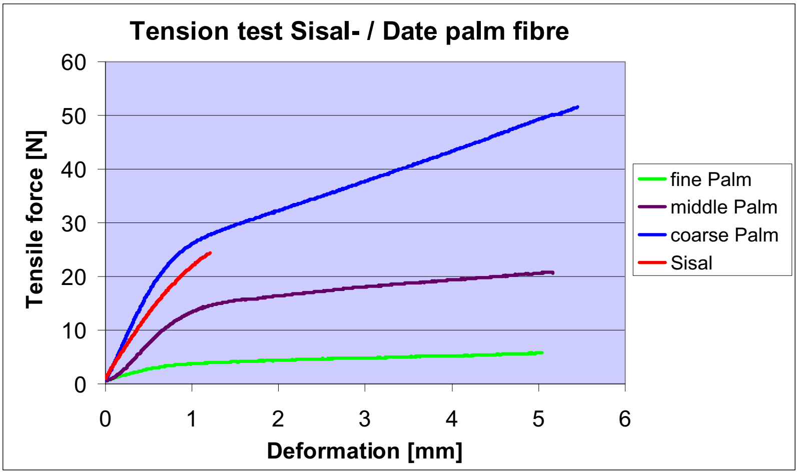

Figure 10: Stress-deformation curves of Sisal and Date palm fibres under tension.

The differences in the tensile strength of the fibres can be explained by aid of the differing functions the fibre plays in the plant. While the Sisal fibres stabilise the leaf structure of the agave plant, the Date-palm fibres mainly have a protective function.

Information regarding the bonding conditions between fibre and clay has been gained by investigating the fibre surface and the integration of the fibre in the clay with the use of an electron microscope.

While the Date palm fibre displays a relatively smooth surface, the Sisal fibre is strongly marked by the remnants of leaf structure. Further scans investigating the integration of the fibre in the clay matrix, display a interlocking of the Sisal fibre surface and clay crystals. Conversely, the clay crystals were obviously unable to interlock in the same degree with the smooth surface of the Date palm fibre.

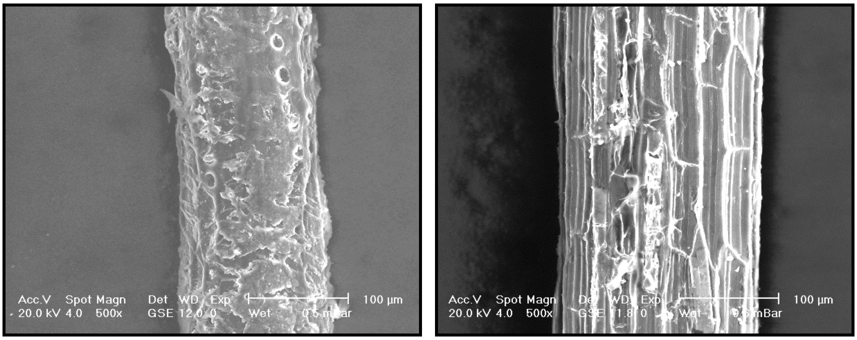

Figure 11: Electron microscope scans of Date palm (left) and Sisal fibres (right).

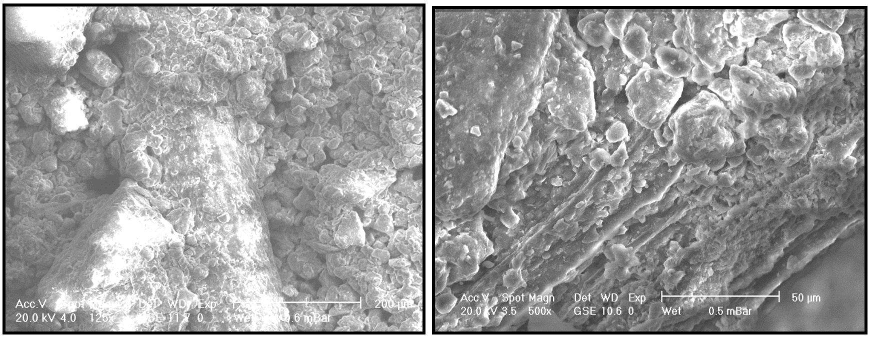

Figure 12: Integration of Date palm (left) and Sisal fibres in the clay matrix (right).

The favourable bonding conditions between Sisal fibre and clay, along with the high tensile strength this achieves provides the basis for the superior tension and compression results achieved with Sisal fibre reinforced clay bricks.

4 Improving the bond between clay mortar and clay bricks

A further method to enhance the shear resistance of masonry is to increase shear and tensile strength as well as the friction coefficient between mortar and brick. Therefore several tension and shear tests of two- and three-stone-specimens with different surfaces and varying additives to the clay mortar were performed on clay brick structures. In addition to the traditional sandy and finger-scratched roughened brick surfaces, smooth, steel-brushed and two different scrapper-prepared surfaces of brick were tested. As additives, cement, lime and gypsum were chosen.

The best results were achieved with surfaces roughened by coarse scrappers and clay mortar mixed with gypsum. The Figure 14 displays the tension and shear strength of the optimized brick surface and clay mortar which is compared

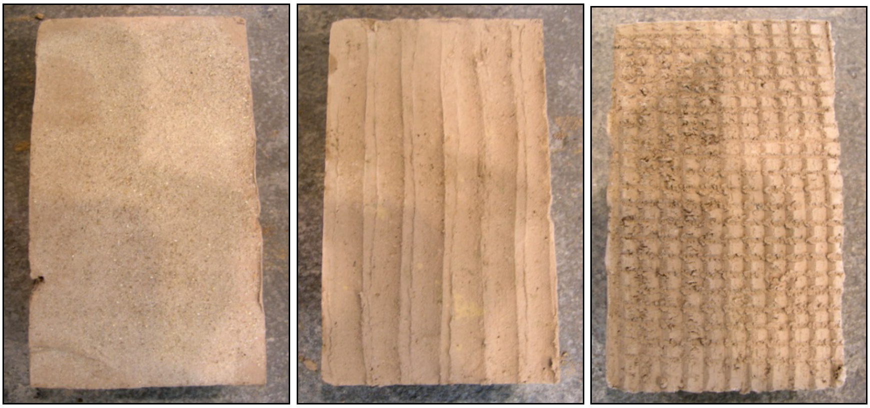

Figure 13: Sandy, finger-scratched and coarse scrapper roughened brick surfaces.

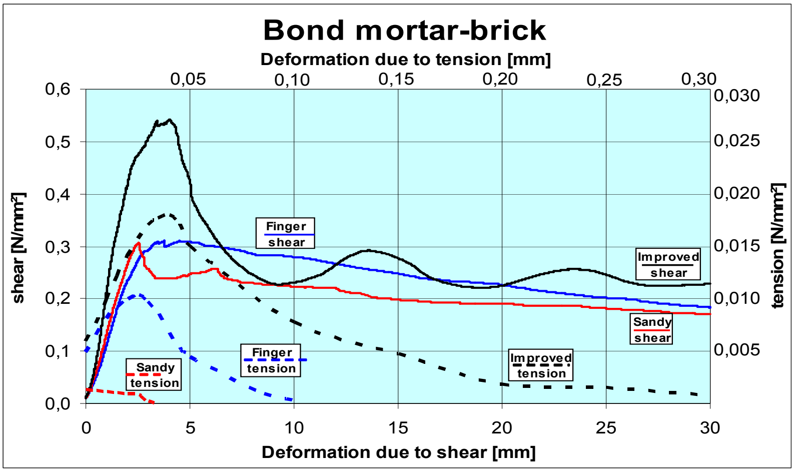

Figure 14: Stress-strain curves of different brick surfaces and clay mortar additives – tension and shear.

to the traditionally used sand and finger-scratched bricks and clay mortar without additives.

5 Shear resistance of traditional and improved adobe masonry

The shear resistance of traditional and improved adobe Masonry were determined according to the Mann/Müller theory [1], using the material properties evident in the previously described tests.

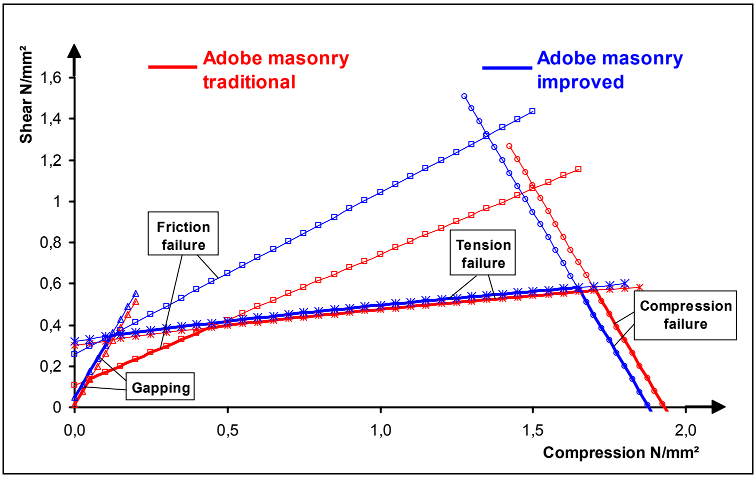

Figure 15: Shear failure criteria for traditional and improved adobe masonry.

Whilst the traditional adobe masonry features all typical criteria for shear failure, friction failure does not appear in the improved masonry material. Conversely there is a wide range of compression, where the tension failure is the decisive criteria, indicating the necessity of a further enhancement of the tensile strength by fibre reinforcement in the clay bricks.

6 Concluding remarks and future research aspects

The described static tests can provide information about material properties, energy absorption capacity and shear resistance, but they are not designed for the accurate determination of the behaviour of masonry under earthquake actions. Additional cyclic tests have been carried out on adobe masonry walls to this end, but are not covered in this paper.

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