Structural Analysis of Historic Construction – D'Ayala & Fodde (eds)

Reconstruction of the Sistani House at Bam Citadel after the collapse due to the earthquake 2003

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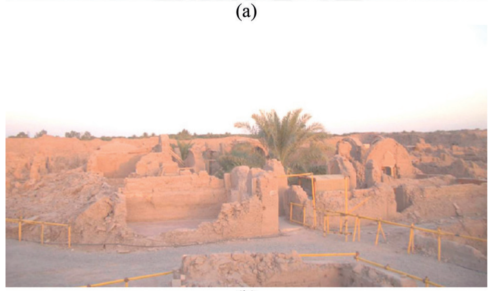
ABSTRACT: In December 2003 an earthquake heavily damaged not only the modern city of Bam, but also the historic site of the citadel, one of the largest adobe masonry structures in the world. As part of the restoration program of the Recovery Project for Bam's Cultural Heritage and in close collaboration with the Iranian Cultural Heritage, Handicraft and Tourism Organization (ICHHTO), the Sistani-House has been chosen as a pilot project for reconstruction with reinforced adobe masonry. Thanks to the funding by the UNESCO, the Japan Funds-in-Trust for World Cultural Heritage and the Cultural Preservation Program of the Federal Foreign Office of Germany, first steps towards a complete rehabilitation of the Sistani House have been taken. These included: Building archaeology, material testing, retrofitting of the preserved walls and earthquake resistant reconstruction of two rooms of the House. The project is to find a sensitive balance between the demands of a world cultural heritage site and modern retrofitting techniques preventing a newly collapse during a future earthquake of the same strength.

1 INTRODUCTION

The citadel of Bam in Iran is one of the most striking complexes of mud brick architecture in the world. Although early settlements can be traced back to the Achemenidian era (559-330 BC), today's appearance of the citadel is largely characterized by the architecture of the past 400 years. The severe earthquake of December 2003 destroyed major parts of the citadel. Also the Sistani House has been damaged to a degree of about 70%. The Sistani House was built in the late 18th century (A.D.) as a rather elaborate dwelling for a wealthy family. The single-storey building consists of two courtyards and displays several very typical features of traditional Iranian desert dwellings (Fig. 1).

As a response to the devastating earthquake, the UNESCO 2004 decided to enlist Bam and its cultural background as endangered cultural world heritage. A plan was to develop as strategy for a rehabilitation of the destructed and damaged historical buildings and surrounding walls of Bam. Within this setting the Dresden University of Technology proposed together with Jäger Consulting Engineers Ltd. a scheme for the consolidation of the preserved remains and a clearly regulated completion of the Sistani House with reinforced adobe masonry. It was a result of the conceptual design and the consideration of the pros and cons of the different variants for dealing with the remains (Jäger & Fuchs 2007).

(a)



(b)

Figure 1. The Sistani House before the earthquake (a) (source: Recovery Project of Bam's Cultural Heritage) and after it in spring 2007(b).

The project has taken off in the second half of 2006 with material tests for retrofitting technologies which should guarantee that the buildings will not collapse once more during a next earthquake of the same intensity.

At the beginning of the project in 2007 the most rubble in the house was removed so that we were not able to draw conclusions concerning the actual process of collapsing (cf. Jäger 2005). But some remaining debris and the ruins allowed us to put forward first hypotheses. The gathered information was used to set up a collapse analysis. A thorough survey of two rooms that were part of a pilot project brought up exact drawings for the further process and gave precious information about the history of the house. Furthermore tests for the production of fibre reinforced adobes were conducted in Dresden as well as in Bam and provided information of the best ingredients and the suitable quota of each. The second half of 2007 was dedicated to the actual building process in the house. After the consolidation works in order to preserve as much of the original substance of the structure as possible, the rebuilding process started. In April 2008 the two rooms of the pilot project were successfully completed.

At all times of the process the project was dominated by the central question: How can we find a suitable, modern answer to the matter of world cultural heritage being endangered by constant seismic activity? How can we find a balance between effective protection against earthquakes and the demands of modern standards of heritage conservation?

The following paper is dedicated to present our approach to this difficult setting and to explain the applied techniques.

2 PRELIMINARY ACTIVITIES

2.1 *Debris removal*

The first step to be taken was the removal of the remaining debris. This process was supervised and organized by a staff of the Dresden University. The basic idea of a carefully and attentively organized and supervised debris removal is to gather as much information as possible about the actual process of the collapse. The gained data helped – together with a mapping of damage patterns – to set up a collapse analysis. Furthermore parts of the interior decoration of the house were recovered and will be – if possible – re-used. These helped to give essential information about the former layout of the house. The supervised rubble removal also offered some information about the building history of the Sistani House, as the debris revealed a surprisingly high density of findings integrated into the masonry. A remarkably high number of fragments of ceramic vessels were also found.

2.2 *Survey documentation of the preserved parts*

The debris removal was followed by a precise survey of the ruins. This survey was initially limited to the extent of two rooms of the pilot project. The survey was conducted with a total station and photogrammetry. The exact survey was necessary because the available plans of the house showed little correlation with the real building and could not be used as a basis for the restoration planning. On the other hand the drawings generated from the photogrammetric images, served as a basis for the mapping of damage patterns. A detailed room-book dealt with the findings on each structural member and documented the pre-restoration state of the construction. At the same time a limited archaeological excavation has been conducted that aimed not only at clarifying the shape and strength of the foundations, but also at gathering more information about the history of the building. A third aim of this excavation was to locate a presumed servants' wing of the house. Yet, in this matter, the excavation has not yielded any information (Mokhtari, Sajadi Hezaveh, 2007).

3 EXPERIMENTAL INVESTIGATIONS

The reconstruction of the Sistani-House is engulfed by two fundamental factors of which all involved parties have to be aware: On the one hand we do have the declared intention that some key buildings of the citadel, including the Sistani-House, ought to be reconstructed because of their historic significance. On the other hand we have to consider the constant threat of future earthquakes. As a result of that a sensitive compromise had to be found that combines modern reinforcement strategies with the special demands of a UNESCO world cultural heritage site.

These requirements asked for a thorough investigation of the process of the collapse of the building and – as a consequence of the results of this analysis – an examination of different approaches towards a strengthening strategy. In springtime of the year 2007 the University of Technology Dresden has conducted a detailed collapse-analysis of two rooms of the Sistani House (Bakeer & Jäger 2007). The results pointed out that the weak point of the traditional adobe brick architecture in which the Citadel of Bam is almost exclusively constructed, is determined by a lack of coherence within the brickwork. Seismic stress has an immediate effect on the weak bonding of the brickwork and caused the almost total collapse of the building. The model furthermore unmistakably proved that a building reconstructed in the same way as before, would certainly not survive a further earthquake. Thus any new approach to the reconstruction of the Sistani House would have to start from enhancing the capability of the masonry to react flexibly to seismic stress without the immediate loss of coherence.

Figure 2. Test specimens for grouting material in the laboratory of the Dresden Technical University (shrinkage of the grouting material in the bore hole).

In order to present a convincing strategy that meets the above mentioned aims, the team of the Technical University of Dresden conducted a wide range of practical tests. These tests referred to the three main columns of the later restoration proposal:

- Retrofitting and strengthening of the preserved remains of the Sistani House after the earthquake,
- production of a reinforced adobe in order to enhance the ductility of the smallest segment of the masonry,
- reinforcing techniques for the new adobe masonry.

3.1 *Strengthening the Preserved Walls of the Sistani House*

The fundamental idea of this part of the restoration plan is, to retrieve as much of the historical substance as possible and to reinstall it as an effective part for the latter reconstruction phase. Yet the earthquake has led to a loss of integrity within the masonry and brought up the necessity to find ways to effectively rehabilitate its load bearing capacity. The damage patterns show a large diversity and range from capillary cracks, to large gaps and debonding along different building phases and elements. Different damage patterns ask for different restoring approaches. The material tests run in the laboratories of the Dresden University focused on grouting techniques and the composition of the suspension as well as on needling and anchoring.

3.1.1 *Identification of suitable grouting materials*

Trying to define suitable grouting materials it was important to restrict the proposal to materials that are frequently used in the Citadel of Bam, such as clay and gypsum. Further tests have been conducted with ingredients as cement, lime or fluids added to the mixture such as potassic and sodium water glass and soda in order to reduce the demand of water (Fig. 2). Specimens were produced and tests on compression strength, bending tensile strength and splitting tensile strength were conducted.

After the completion of the test row it was decided in favour of a suspension of water, clay powder, a low ratio of lime and a very low ratio of natural wallpaper paste as plasticizing agent.

3.2 *The grouting of cracks*

Also the actual grouting process was tested practically in the laboratory of the Dresden University (Fig. 3). A test wall of adobe masonry was built displaying the typical damage pattern of large diagonal cracks. The crack was superficially closed with clay mortar before the clay suspension of the above mentioned composition was injected with a grouting pump.

3.2.1 *Needling and anchoring*

The needling and anchoring represent techniques designed to repair larger cracks (Fig. 3). Several adobe walls were built in the laboratory of the Dresden University in order to run tension strength tests to identify a suitable anchor material. The anchors were placed in 30 mm boreholes and fixed with the chosen grouting material.

The chosen glass fibre rods show the advantage, that it is chemically stable, not affected by termite infestation, has a low modulus of elasticity in comparison to steel and does not corrode.

3.3 *Developing fibre reinforced adobes*

The aim of this test row was to enhance the ductility of the brittle building material clay in order to improve the dissipation of energy within the adobe masonry under seismic action. Furthermore it was intended to improve the resistance of the adobes towards termite activity taking into account that the ecological qualities of the material ought to be unaltered.

After running a test row with sisal, coconut, flax, hemp and palm fibres it was decided to present palm tree fibres as suitable material to reinforce adobes. The palm fibres have the additional advantage of abundant

local availability: Palm tree fibres are a side product of the extended date growing gardens; the material is normally simply burned. Tests have proved a considerable increase in compression and tensile strength (Fig. 4). These tests were equally executed in the laboratory in Dresden as well as in Bam itself, in order to produce the adobes under real circumstances and with locally available material.

The results enabled us to name the exact quota of the ingredients clay and sand (70 : 30) and fibres (0.6% of the weight of the sand-soil compound).

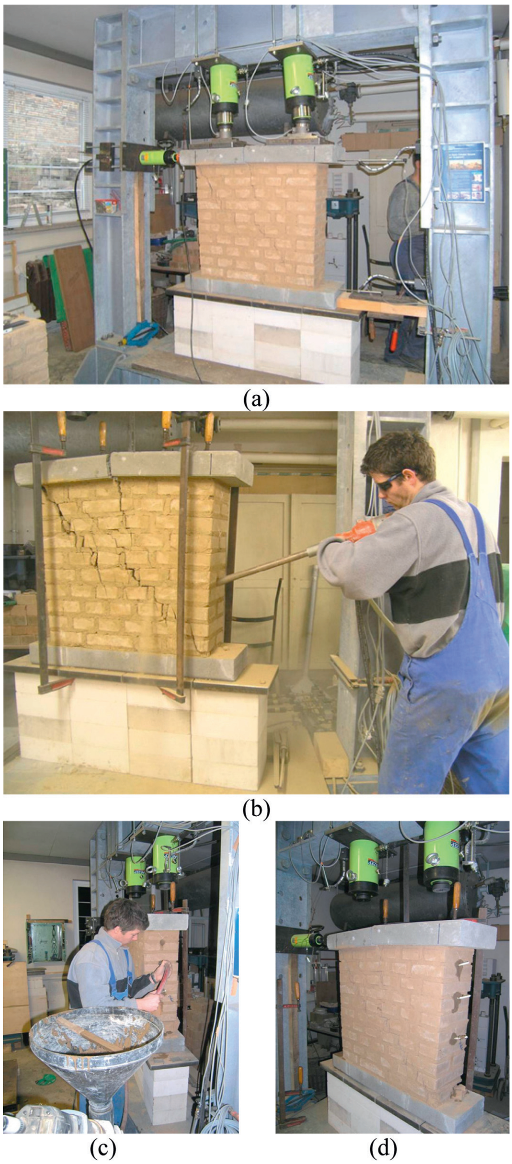


Figure 3. Test row for the repair of large cracks by needling with fibreglass rods. The figure (a) shows the test wall of adobes while a typical failure pattern (large diagonal crack) is being generated. The figure (b) shows the drilling of the holes in which the anchors will be inserted. On the figure (c) the fibreglass rods have been inserted and the boreholes are grouted. The figure (d) shows the repaired wall.

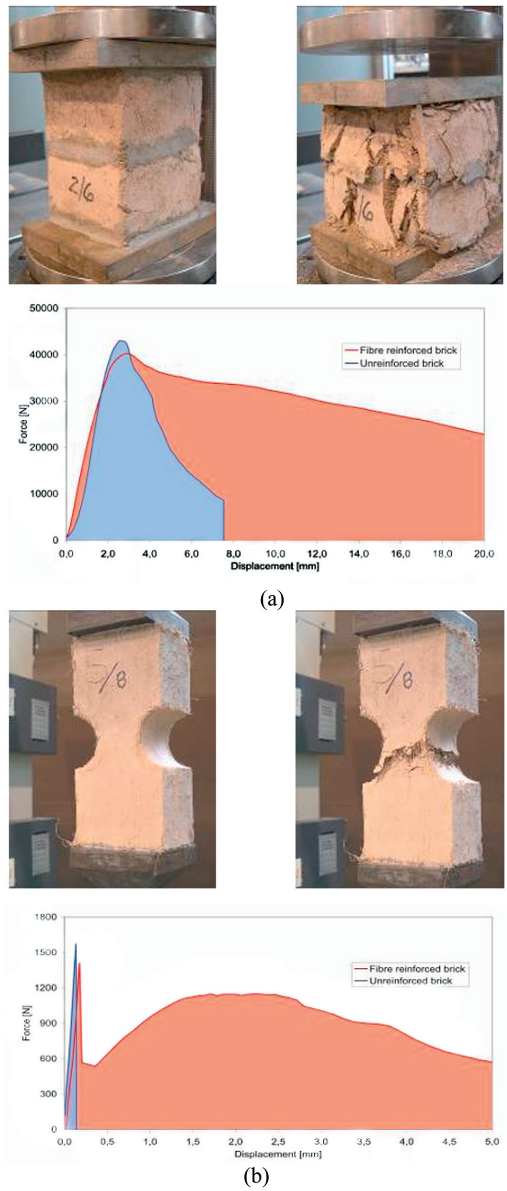


Figure 4. Laboratory tests proofed higher ductility under compression (a) and tension (b) of palm fibre reinforced adobe units.

3.4 *Techniques for reinforcing new adobe masonry*

The reinforcing strategy for new adobe masonry bases majorly on the results of the pull-out tests with the fibreglass rods and the collapse analysis (Bakeer & Jäger, 2007). The information obtained from the tests and the model enabled us to calculate necessary reinforcement measures that help the building to withstand an earthquake of similar force as the one of 2003 (Fig. 5). In this way it was not only possible to describe the necessary reinforcement but also to quantify the required material. The reinforcement trials suggested vertical and horizontal anchors of glass-fibre, a ring beam on the level of the impost of the vaults and glass fibre mesh in order to strengthen horizontal masonry joints.

So it can be guaranteed that the whole building will not lose its integrity during a next earthquake.

Crossing bars will be fastened with binding wires from stainless steel.

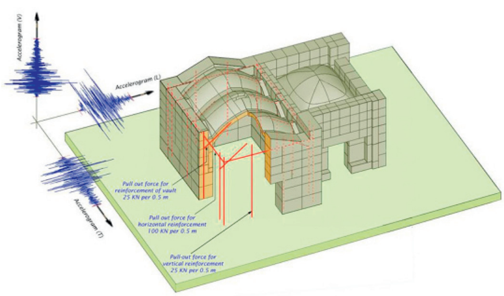


Figure 5. The Location of vertical, horizontal and vault reinforcement (represented within the numerical model).

4 IMPLEMENTATION

4.1 *Consolidation of the preserved walls of the Sistani House*

In July/August 2007 the first part of the preliminary tests and surveys came to an end and the actual consolidation process was put into practice. The consolidation covered all above mentioned steps of closing cracks, grouting and insertion of needles and anchors (Fig. 6).

The closing of the cracks was conducted according to the tests under laboratory conditions. As a first step they had to be cleaned. Debris and dust was removed to have a clear open gap with no loose parts.

In a second step locally available clay was mixed with water in order to create a paste-like consistency with which the cracks were superficially closed. A plastic pipe with the diameter of the neck of the injection pump was inserted into the crack in regular intervals of about 25 cm in order to create openings for the following injection of the grouting suspension.

The grouting suspension was composed as described above. In order to prevent the suspension to dry up too quickly the grouting was only carried out at early morning and late afternoon because of the very high temperature at the building site. It was done according to the rules for grouting of historic stone masonry and with a pressure no higher than 2 bar.

As a second step of the consolidation works, the glass fibre anchors were inserted into walls that showed large vertical cracks running orthogonal to the axis of the wall. The segments of these walls threatened to lose their coherence and to break apart in direction of the axis of the wall. The horizontal anchors are designed to permanently stop this movement and to re-establish the load bearing capacity of the structural member.

Figure 6. Grouting process in situ. On the left the cleared crack; the central figure shows the process of closing the cracks with clay leaving small holes for the subsequent injection into the cracks, figure on the right.

Just as shown in the laboratory tests, the anchors were inserted into boreholes, fitted with threaded steel rods on both ends and then braced with two steel plates on both ends. The borehole with the braced anchor is grouted in order to achieve a good interconnection of anchor and masonry.

4.2 *Production of palm fibre reinforced adobes*

In order to prepare the subsequent works of reconstruction it was necessary to start a large scale production of palm fibre reinforced adobes proposed by the earlier test series. Geological tests executed by the Iranian Cultural Heritage, Handicrafts and Tourism Organization (ICHHTO) have determined a suitable quarry for clay in a small city about 25 km south of Bam. Further tests conducted by the Dresden University of Technology have shown that the content of salts does not exceed the recommended quota. It was thus decided to bring the soil from there to the adobe production site close to the Citadel of Bam. The palm fibres were easily available but had to be processed in order separate the fibres from each other and to cut them into an appropriate length of about 4 cm. This processing was done by a cutting machine that was bought just for this process. Experience showed that it was very important to look after a good distribution of the fibres in the compound. The mixing of soil, sand and fibres was carried out in a dry state (Fig. 7, below). In a second step, water was added and the compound was left for three days to achieve an ideal malleable texture of the material. On the third day the compound was mixed another time and the adobes were produced with wooden moulds. The fresh adobes are not to be exposed to direct sunlight for one week to prevent them from cracking; the further drying process takes about three weeks. In order to improve the regularity of the masonry on the building site, it was decided to produce, apart from the traditional square shaped $25 \times 25 \times 4$ sized adobes, also a half size (Fig. 7).

4.3 *Insertion of the vertical anchors*

Before the actual reconstruction of walls and vaults in the Sistani House could begin, the vertical anchors of glass fibre had to be inserted. In preparation for that, the walls were brought up to an equal level by removing rests of unsustainable masonry and repairing damaged wall segments with the newly produced fibre reinforced adobes. A scaffolding was installed alongside the walls upon which the core drilling machine for the vertical boreholes was mounted. These were drilled in an interval of about one metre, have a width of 10 cm and reach down to a depth of -1.50 m below ground level. The vertical anchors consist of three glass fibre rods with a diameter of 8 mm. On their lower end the bundle of three rods is spliced up; it is inserted into a

Figure 7. Production of palm fibre reinforced adobes in Bam.

block of fine concrete that ties the vertical anchor to the ground. The rest of the borehole is filled with the same clay suspension that was used for the grouting in the consolidation phase.

The vertical anchors reach up to the highest parts of the walls (Fig. 8, below).

4.4 *Building with horizontal reinforcement*

The horizontal reinforcement consists of two parts: Every 0.50 m in height a layer of fibreglass mesh is inserted into the horizontal joint in the masonry. In addition to that, a horizontal rod of fibreglass is fixed to the vertical anchors.

On the height of the impost of the vaults a ring beam composed of six fibreglass rods (width 0.60 m, height 0.30 m) is constructed and bricked up.

4.5 *Reinforcement of the vaults*

To improve the inner integrity of the masonry of the vaults, it was decided to wrap the transversal arches as well as the sectroids of the vault with the same fibreglass mesh that is being used for the horizontal joints. The mesh will be covered by the traditional clay plaster.

Figure 8. View of the building site of the Sistani House. January 2008.

5 STATE OF THE PROJECT – PERSPECTIVES

The first measures of planning, consolidation and reconstruction were limited to two rooms. This pilot project was intended to clarify possible problems implementing the rehabilitation strategy that has so far been tested only under laboratory settings. All working steps up to the construction of the vaults have been carried out successfully. The vaults are momentarily being completed. The technical realization of the project showed only few problems, and can, without any doubt, be applied for the continuation of the project.

As the project has been granted further funding by the Cultural Preservation Programme of the Federal Foreign Office of Germany, the works will be extended to further nine rooms. After the completion of these rooms at the end of 2008 the Sistani House will be restored to a degree of about 60%.

Parallel it is planned to continue research on different topics: Constant quality check of the produced palm fibre reinforced adobes, proof of termite resistance of the adobes, climatic check up of the building aiming at a sensible re-use of the wind towers for natural air conditioning and continuation of archaeological research.

It is our clear aim to conclude the works on the Sistani House by the end of 2009 and contribute to the lively discussion of how to face the matter of rehabilitation within a world heritage site.

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