Seismic retrofitting of adobe masonry buildings based on collapse analysis

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Abstract

A novel approach is presented for retrofitting and reconstruction of cultural heritage buildings based on collapse analysis. The computer modelling is carried out through LS-DYNA code, where the combined finite/discrete element method is adopted. The approach is applied for two rooms in Sistan’s house in Bam citadel, which collapsed under the earthquake of 2003. The proposed methodology is used to verify the retrofitting measures that were implemented into the structure to resist the forthcoming earthquakes. Further experimental investigations are performed to enhance the performance of adobe material under earthquake actions and the determination of the suitable reinforcement materials is achieved.

Keywords: adobe masonry, collapse analysis, macro modelling, combined FEM/DEM, explicit dynamics.

1 Introduction

Bam Citadel (Arg-e Bam) is one of the largest adobe complexes in the world and plays an important role in the history of Iran. The citadel which is traced back to the Achaemenid period (6th to 4th centuries BC), and is considered the most representative example of a fortified medieval construction built by adobe masonry. The citadel is situated atop a hill in the northwest old city of Bam on an area of 180,000 square meters. Bam Citadel was destroyed during an earthquake in December 2003. Immediately after the disaster, activities were started to preserve the destroyed monument site and to clear the question how to deal with the remains. UNESCO included the Citadel with its unique surroundings and landscape in the list of World heritage sites under risk. Now the consolidation, restoration and reconstruction are under progress.
Several efforts were made by the Iranian authorities and the international community to reconstruct the collapsed citadel. Within the framework of reconstruction of the Bam citadel by international experts, our German team undertook a part in Sistani’s House. In order to develop a strengthening methodology for Sistani’s House, two rooms R 0.11 and R 0.12 in the northwest corner were selected as the pilot project (fig. 1).

![Diagram of Sistani's House](image)

Figure 1: Sistani’s House, (a) the ground plan, the selected part for the pilot project marked in red (b) 3D model of the house, Einifar [1], (c) Sistani’s House after the earthquake of 2003; the debris inside the rooms is removed.

2 **Investigations of the damage and reasons for collapse**

Several processes are carried out in situ, starting with the removal of the debris and survey documentation of the ruins. The key question to be answered is the allocation of the fallen debris to its original built-in position. Following that, it becomes possible to analyze the process of the collapse in order to verify the vulnerability of the structure.

The survey was performed by a total station and photogrammetry. The drawing generated from the photogrammetric images served as a basis for recording the situation of the damage; it also gives essential information about the original form of the house. The damage patterns show a large diversity and range from capillary cracks to large gaps and debonding along different building phases.
The remains and the damage patterns observed in situ indicate that the collapse initiated due to out of plane failure of the walls. Such failure could be a result of the vaulted roofing system which has high vulnerability to collapse under horizontal earthquakes.

3 Principles of dealing with remains and reconstruction

The enormous size of the destruction in the citadel is associated with the weak brittle material of adobe masonry. It is difficult in such situation to find the appropriate solution for the restoration, reconstruction and retrofitting of the highly damaged architectural heritage. However, some guidelines that match the special demands of modern UNESCO world cultural heritage site are adopted for the reconstruction process.

At first, it is essential to retrieve as much as possible the remains of historical substance to reinstall them as effective part for later reconstruction phase.

The behaviour of brittle material such as adobe masonry could be enhanced by increasing the ductility which offers the ability to prevent sudden collapse. The presence of a vaulted roofing system is the reason of the overall stability of the structure being lost during the earthquake. Therefore, the implementation of ring reinforcement is of high importance.

4 Collapse analyses as tools for verification

In order to explore the performance of the structure which collapsed under the earthquake of 2003, a collapse analysis is carried out by means of LS-DYNA code [6].

The elements of the structure (thick walls, vaults and piers) comprise a large number of bricks. Therefore, the generation of the geometry brick by brick will be highly time-consuming; furthermore, the geometry of the bricks is not known beforehand. As a result, micro-modelling cannot be applied in such a case. An alternative approach that can overcome the problem is to employ macro-modelling, which needs a small modelling effort for large structures. It reduces the model size and calculation time as well.

In adobe masonry, mud mortar has been used to assemble the mud bricks. This points toward getting material continuity in between the brick units and mortar as well as approximately similar mechanical characteristic for masonry in orthogonal directions.

Since the structure is already destroyed by the earthquake of 2003, the definition of geometry is based on the available data in situ, that is, the remaining parts, and the available pictures before the collapse. The whole geometry of the structure is divided into discrete elements by means of CAD tools (fig. 2).

Each pair of two adjacent discrete elements is sharing a contact interface which ties both interface elements prior to the failure. This tends to generate separation of the tied discrete elements when failure of contact takes place. Those interfaces are representing the locations of potential cracks. Without those
interfaces the calculation process terminates, due to large deformations of finite elements at failure. LS-DYNA tiebreak contact model has been used to model the planes of failure. Tiebreak contact is active for nodes which are initially in contact. The slave nodes are sticking permanently until reaching the failure criterion. After failure, this contact option behaves as frictional contact.

The discretization is performed in a regular manner so that regular geometrical shapes are produced and acute angles are avoided; the later cause problems with the handling of contact (fig. 3(a)). In addition, mapped meshing is applied comprising eight-node brick finite elements with a single integration point (fig 3(b)). This prevents the negative volume problem at an early stage, which terminates the calculation in explicit solvers.

The LS-DYNA soil and foam constitutive model has been employed for modeling the material of adobe masonry. The material properties used in our model are based on values adopted by Taheri [3], Kiyono and Kalantari [4] and in [2].

The collapse analysis of the structure shows that the collapse initiates in the longitudinal direction of the earthquake; this can be explained by the high acceleration at the beginning of earthquake (fig. 4). A few seconds later, the
walls perpendicular to the transversal earthquake direction are collapsed. At this time, there is an increase of earthquake intensities along transversal direction which can explain this collapse. The order of collapse sequence as noted in collapse analysis is identical to that predicted by the investigations on the ground. The falling debris on the ground show clearly that the direction of the collapse is mainly along east-west direction. At the last stage of the analysis, out of plane failure of the walls is the main failure mode, which fits with results described by Kiyono and Kalantari [4], for adobe masonry buildings in Bam. The relatively high value of friction coefficient 0.54–0.62 causes this mode of collapse.

5 Reinforcement of the building

The results of collapse analysis have showed that collapse was mainly initiated due to out of plane failure of the walls. This kind of failure is possible in such structures due to vault-form construction of the roofs. Therefore, the capacity of the structure can be enhanced to resist out of plane actions by implementing ring reinforcement. The vertical reinforcement enhances the integrity and the load bearing capacity as well.

Fibreglass nets with clay-cement grout are supposed to be used as reinforcement; a series of pull-out tests have been carried out in order to determine the proper reinforcement and the grout material to be used with adobe masonry [2]. The reinforcement was built in 36 cm into the wall, which is the tested anchor length. For a standard fibreglass net built into a borehole \( d = 30 \text{ mm} \), the average maximum pull-out force for clay-cement grout was 9 kN (fig. 5).

In order to simulate the pull-out failure of reinforcement, a breakable bar linked to masonry elements via nodes along the reinforcement locations have been used. Although LS-DYNA provides various possibilities for modelling the reinforcement, each has its own drawback. However the spotweld linkage has been defined along a string of nodes that belong to each reinforced discrete element. The distance between the pair of nodes linked by spotweld is 0.5 m.

The calculation of resisting reinforcement has been performed in iterative scheme. Several reinforcement trials have been tested by collapse analysis on Room 11. Fig. 6 shows the reinforcement arrangement (horizontal ring

Figure 4: Collapse state of the structure at time \( t = 18.80 \text{ s} \).
reinforcement, vertical reinforcement, and vault reinforcement) that was used for calculation trials. The spotweld failure values of the reinforcement are given in table 1.

![Figure 5](image1.png)

Figure 5: Pull out test of reinforcement (a) test setup, (b) pull-out force versus displacement plot for different anchoring types [2].

<table>
<thead>
<tr>
<th>Trial No.</th>
<th>Maximum bonding force (kN/50 cm)</th>
</tr>
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<tbody>
<tr>
<td>#1</td>
<td>10</td>
</tr>
<tr>
<td>#2</td>
<td>50</td>
</tr>
<tr>
<td>#3</td>
<td>100</td>
</tr>
<tr>
<td>#4</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 1: Reinforcement bonding capacity.

![Figure 6](image2.png)

Figure 6: Reinforcement arrangement for Room 11.
In the 1st trial, vertical and horizontal reinforcement were added to the walls; the final remains showed that some walls remained intact at the end of earthquake and others collapsed partially and the vault collapsed due to progressive collapse. The reinforcement was sufficient for some walls, but must be increased for others. We have to consider that the creation of new strong parts by reinforcement may change the collapse mechanism. In the 2nd trial, the horizontal ring reinforcement was increased, but that was not sufficient and the ring reinforcement failed. In the 3rd trial, the walls of the room showed good stability but the vaults partially collapsed and showed large deformations. Thus, one task that should be achieved as a next step is to add reinforcement to the vaults (fig. 7).

6 Improving the ductility of units

To improve the ductility of adobe material, adobe units are produced with sisal, coconut, flax, hemp and palm fibres and a series of experiments were carried out to decide the suitable material of reinforcement.

The tests were performed in a Dresden laboratory as well as in Bam, in order to obtain results under real conditions. The results led to the recommendation of the use the ratios of clay and sand (70: 30) and fibres (0.6% of the weight of the sand-soil mix). The tests showed no increase in compressive and tensile strength. The stress-displacements relationship from the compression and tension tests showed considerable amount of deformation prior to failure. This indicates an enhancement in the ductility of the material of the units (fig. 8).
7 Implementation of the reinforcement

The remaining walls are repaired first with the fibre reinforcement and the walls are brought up to an equal level by removing remnants of unsustainable masonry. Following that, vertical anchors of glass fibre are inserted as described by Jäger and Fuchs [5].

Scaffolding, upon which the drilling machine for vertical boreholes can be based, is installed next to the walls. Boreholes are drilled at an interval of 1 m and reach down to a depth of 1.5 m below the ground level. The vertical anchor consists of three fibre rods with a diameter of 8 mm. At its lower end, the bundle of three rods is spliced up. It is then inserted into a block of fine concrete that ties the vertical anchor to the ground. Horizontal reinforcement layers of fibreglass mesh are added, each at 0.5 m height. A horizontal rode of fibreglass is fixed to the vertical anchors as well. The ring beam reinforcement of the vaults consists of six fibreglass rods (width 0.6 m, height 0.3 m). For the vaults, the transversal arches are wrapped with the same fibreglass mesh that is used for horizontal joints and covered with traditional clay plaster (fig. 9).

8 Summary and outlook

A novel approach is presented for retrofitting and reconstruction of cultural heritage buildings based on collapse analysis. The approach is applied for two rooms in Sistan’s house in the Bam citadel which collapsed under the earthquake of 2003. The proposed methodology used to verify the retrofitting measures that were implemented into the structure to resist the forthcoming earthquakes.
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References


