DIGITAL 3D RECONSTRUCTION BASED ON ANALYTIC INTERPRETATION OF RELICS: CASE STUDY OF BAM CITADEL

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ABSTRACT:

We explain our approach to 3D modelling of architectural heritages that were destroyed in a natural disaster. The heritages in question are not properly documented and their original shapes are not easily ascertainable. Our case study is the Citadel of Bam, a UNESCO world heritage in danger in Iran that was destroyed in an earthquake in 2003. Documentation on the site before its destruction is scarce, and the original shapes of many buildings cannot be precisely recovered from 2D drawings made before the destruction. In many cases, complementary information for the 3D modelling can be derived from other heterogeneous data such as photos, 3D cartographic map, etc. However the available heterogeneous data on some unimportant parts of buildings and rooms do not always directly reveal the original shapes and geometries of spaces, and hence, the original shaped have to be estimated with the help of analytic interpretation using surviving relics. In some ambiguous situations, the remains of one destroyed vault, cupola, wall, window or door can help us to understand what the complete artefact had looked like. The symmetry of architectural elements, characteristic construction methods, and similar tendencies of renovations were of help to make analytic interpretations about what had existed.

1. INTRODUCTION

The Citadel of Bam is a huge adobe architectural complex in the historical city of Bam. It is situated along the Silk Road in southeast Iran (Mehriar, 2003). This UNESCO world heritage site in danger was almost completely destroyed in an earthquake in 2003. Physical reconstruction of the citadel will be a great challenge, because most buildings on this huge site (180,000 square meters) were destroyed or are now dangerously unstable.

The National Institute of Informatics (NII) in Tokyo proposed to undertake a digital reconstruction and virtual reality of Bam Citadel as part of the Digital Silk Roads (DSR) project (Ono, 2005). The revival of this heritage in a virtual world was considered to be a quicker, cheaper, and more practical solution in comparison with a real-world reconstruction.

The main task of the digital reconstruction since 2005 has been the 3DCG modelling of various buildings. The complexity of free-form adobe surfaces is the reason that the models have been made in the 3ds Max® environment (Ono, 2008; Andaroodi, 2007a). The large number of buildings, different levels of importance, and lack of appropriate documents for 3DCG modelling are reasons for dividing the citadel area into low, moderate, and high levels of importance for modelling. The buildings in high importance areas have been manually recreated while those in other less important areas were modelled automatically or semi-automatically. The manual 3DCG modelling was done in two phases. The first phase included 3DCG modelling of ten (most of them public) buildings in flat areas. The second phase focused on the hilly upper quarter of the Citadel. Buildings in this quarter included the governor's quarters and had complicated shapes (Matini, 2008).

2. MANUAL 3DCG MODELLING

Digital 3D modelling of the interior and exterior spaces of destroyed architectural heritages can often be done on the basis of 2D drawings (plans, sections and elevations). However, lack of precise 2D drawings for many of the buildings of the Citadel has made it necessary to use heterogeneous data in the 3DCG modelling. Such heterogeneous data can help us to find out more information about the spaces to be modelled, but it is not always easy to use. Our experience in the first phase of 3DCG modelling impressed upon us the complexity of this undertaking. To avoid the problems we encountered in the first phase, we approached the second phase by combining heterogeneous data into a unified data as a basic 3D drawing for the 3DCG modelling.

2.1 First phase

In the first phase of manual modelling from 2005 to 2007, the 3D modellers used heterogeneous data such as 2D drawings, on-site and aerial photos, movies, 3D cartographic maps, sketches, expert knowledge, etc (Andaroodi, 2007b). Simultaneous application of these data led to confusion about

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the domain knowledge, partly because the 3D modellers were not experts in Persian traditional architecture. The modelling process was very slow and the results had many errors, as identified by experts in different periods that had to be modified or remodelled.

2.2 Second phase

To overcome the problems of the first phase, the second phase that began in October 2007 involved developing a unified and precise data. The unified data combined all the heterogeneous data and was developed by an architect with knowledge about Persian traditional architecture. It represents the geometrical character of the buildings and is composed of CAD-based 3D drawings of buildings (wireframe models) that can be easily imported to the 3ds Max® environment and completed with appropriate surface modelling methods by the 3D modellers (Matini, 2008; Matini, 2009).

3. CAD-BASED 3D DRAWINGS

Simply combining the heterogeneous data into a unified form was initially thought to be an adequate way to develop a precise 2D drawing with all the necessary information for the 3D modelling. This solution, however, turned out to be inappropriate because the free-form architectural elements of the adobe constructions in the Bam Citadel cannot be easily represented by 2D drawings. In many cases, we needed several plans, sections, and elevations to get an understanding of the space. We found that the best solution was to develop a 3D drawing that represented the geometrical character of a complicated adobe construction in three dimensions.

We developed this 3D drawing in the AutoCAD® environment, because this engineering software is easier than 3ds Max® to make a 3D drawing with precise coordinates and the result can be imported to 3ds Max®. The 3D drawing is a wireframe model that shows the borders of the architectural elements.

Although the heterogeneous data consists of appropriate 3D information about the buildings, it still had ambiguities and other problems that made it difficult to use. For example, there were dimensional incompatibilities between different 2D drawings and errors in their coincidence with 3D cartographic map and photos. The available 2D drawings for recognizing the complete shapes of buildings were insufficient; different on-site photos taken from the same angle show various periods of restoration, and they needed to be prioritised in the 3D modelling process. In addition, there were few photos of interior spaces and less important buildings, and the photos were mostly of low resolution. The scale of the aerial photos was not fine enough for recognizing small elements, and the facades weren't usually visible in them. The 3D cartographic map had to be modified and its lines adjusted before it could be used for 3D modelling. Finally, there are no oral or textual references about several parts of the Citadel.

These problems and ambiguities led us to experts in 3D ACAD modelling and familiar with historical mud brick architecture in Persian desert cities. These experts could comprehend the content of our task and knew the chronology of the data and the original shapes of the buildings. The drawing is developed in a process with different stages of modifications. A 3D drawing initially drawn from the heterogeneous data and completed through geometrical, structural, proportional, and detail modifications was then used in the final 3D modelling.

4. ANALYTIC INTERPRETATION OF RELICS

The heterogeneous data from before the earthquake usually showed important or easy-to-access parts of buildings. We often lacked enough pre-earthquake information showing the original shape or with which we could estimate the proportions to make a complete 3D drawing of a big or complex building. In these cases, the only possibility for recovering the original shape, proportions and details of spaces was to study the relics that survived the quake. At the beginning of Bam Citadel 3DCG modelling, it was agreed that the 3D models should be based on the last renovation of the buildings. For this reason, we used the relics as complementary information for the 3D drawing.

There are two ways to use relics: directly or indirectly. Sometimes a space, detail, or part of a building remains and we could complete a 3D drawing by directly inspecting it. Although the Bam Citadel was devastated, parts of several buildings, in particular, the layout of the ground floors remained intact.

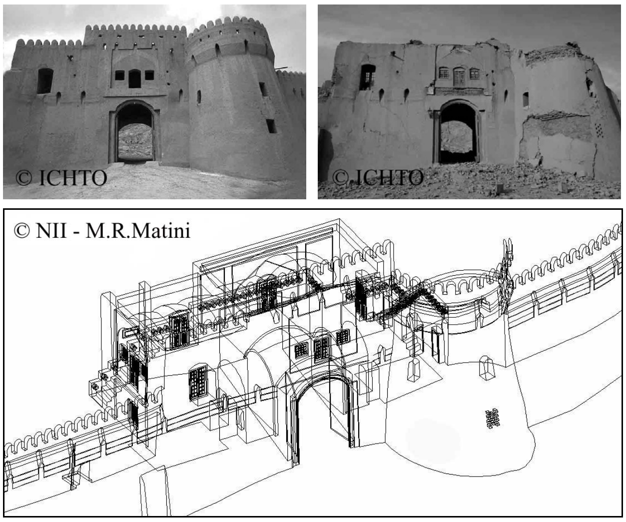

Figure 1. Top-left: Second Gate before earthquake
Top-right: Second Gate after earthquake
Bottom: CAD-based 3D drawing of Second Gate

Figure 1 shows the situation of the Second Gate of the Citadel before and after the earthquake. The South side of the building remained relatively intact. Although the upper parts of the walls and mud and straw finishing layers of the towers were destroyed, some elements that were not evident in the pre-quake photos remained to be documented. The relics show that the building in the condition of its last renovation had windows and a network of mud bricks making an opening in the wall. These details were surveyed after the quake and used for modelling.

The Second Gate was a rare, well-preserved example that enabled us to make direct use of relics in the 3D reconstruction. But the relics cannot be used directly in the case of other buildings that suffered heavy damage and were not well documented. For such buildings, we had to rely on indirect signs or indicative elements to help us to reconstruct the original shape of the space. Through an analytic interpretation of the relics, we could estimate the situation of the architectural space before the destruction.

Our interpretations of the relics were classified according to symmetry, construction method, and renovation period.

4.1 Symmetry

Symmetry plays an important role in historic Persian architecture. Often because of structural or aesthetic aspects, symmetry can be seen not only in architectural elements such as walls, roofs, windows, etc., but also in the whole composition. Our symmetry-based interpretations were thus related to building elements and whole buildings.

4.1.1 Symmetry of architectural elements: Some of the rooms and spaces lacking data from before the earthquake were only partially destroyed. If the rooms consisted of symmetrical elements, these surviving parts of roofs, walls, decorations, openings, and other elements could help us to guess the shapes of the destroyed parts. Figure 2 shows an example of one room in the Small Caravanserai. Almost half of the arch, doorway, and niche remain, and we can guess the shape of the other half of this wall. The 3D drawing of this part was based on our interpretation of these symmetric elements.

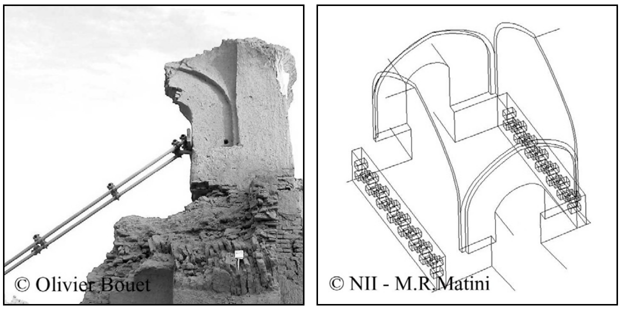

Figure 2. Left: A room in the Small Caravanserai
Right: CAD-Based 3D drawing of this space

4.1.2 Symmetry of whole building: Some of the buildings have nearly symmetric plans that rooms and elements on one side of their courtyard almost mirrored on the other destroyed side. That meant that our interpretation for making the 3D drawing could be based on the similarity between the destroyed side and the intact side. For example, in Figure 3, it can be seen that two sides of the Small Caravanserai's courtyard were destroyed but the other two sides escaped major harm. Although the shapes of the rooms and elements on the north and south sides were not completely the same, there are considerable similarities between them and also between the west and east sides of the courtyard.

We hence used the shapes of arches, networks of mud bricks lining corridors, the structures of the roofs, the facades, and other details of the undamaged sides of the courtyard to correct or complete the data for the 3D drawing.

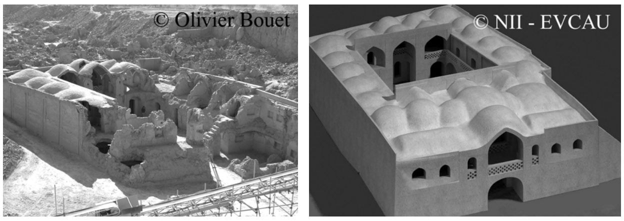

Figure 3. Left: Small Caravanserai after the earthquake
Right: 3D model of this building

4.2 Construction method

Each building material (mud brick, wood, stone, etc.) must be used in a specific shape in a building that it is related to the characteristics of material. These characteristics define the specific method of construction. Therefore, there is a close relationship between material, construction method, and shape. This relationship can help us to recover the original shapes of destroyed elements such arches, vaults, domes, openings, niches in walls, windows, and doors. 'Construction method' can be used to classify the structures of roofs, details of walls, details of windows and doors, and details of facades.

4.2.1 Structure of roofs: The buildings of Bam Citadel have certain types of vaults and domes that make structure of roofs. We prepared an archive of these structures that can be used for 3D drawing. Although the roofs of different buildings will have various orientations and proportions, they have certain shapes that we specified in our archive. In a destroyed roof, if we can verify its structure for covering the space and borders of the space in the plan, we can imagine the original shape and draw it. The height of the roof and its thickness can be estimated from the 3D cartographic map. Aerial photos can help to verify the correctness of the modelled roof. Figure 4 shows a room of Sistani House. The roof was completely destroyed, but remaining walls helped us to recognize the original structure of the roof (a combination of arches and vaults). The 3D model was based on our interpretation of this roof.

Figure 4. Left: A room in House of Sistani
Right: 3D model of roof of room (POV from below)

Figure 5 shows three other roof styles, shown as lines in different 3D drawings. In some cases, the shape of a roof (such as a barrel vault) can be adequately demonstrated with the borderlines only, but in other cases extra lines are needed for showing the curvature of a roof (such as a cloister vault).

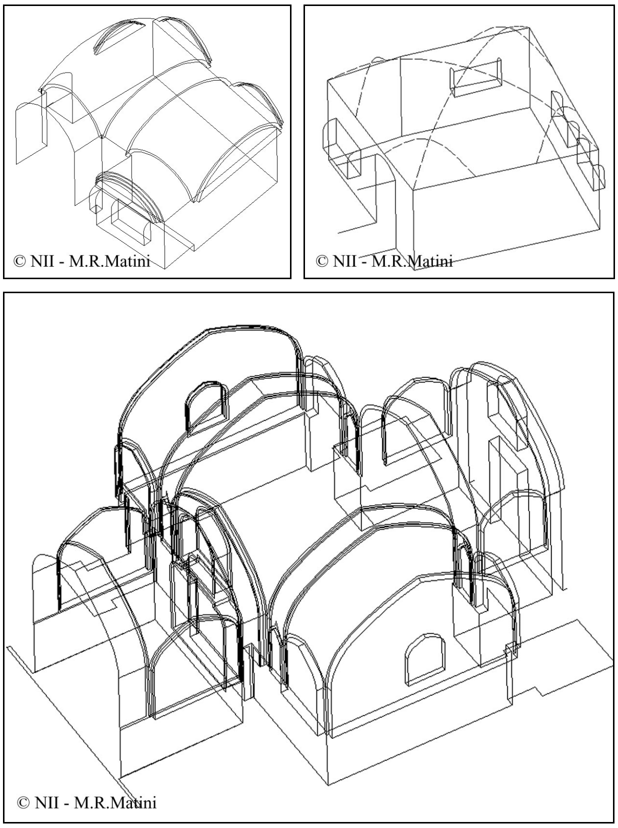

Figure 5. 3D drawing of three different roofs

4.2.2 Details of walls: Mud brick walls are usually very thick, because they must carry weight of roofs and resist the side pressure of vault and domes. But the parts of the wall do not necessarily need to have the same strength. For this reason, Persian historical architecture reduced the thickness of walls in niches. These niches in the Citadel have specific shapes and usually have an arch as a structural element. The arches in niches that resisted the weight of the wall have different forms and directions. Besides niches, openings such as doorways and windows are architectural elements to lighten a wall. Figure 6 shows three walls with different kinds of niches. It is important to consider that in a wall often there is only one kind of element and it is rare to find different kinds of niches or arches for openings. The height and position of elements in a wall needs to be considered too. As you can see in Figure 6, it is common that top lines and bottom lines of one kind of element in a wall be the same in the whole room. We used these features to guess the original shape of a destroyed wall. Even if only one element in a wall can be recognized, other elements of the same kind can be drawn.

Figure 6. Three examples of different niches in different walls

4.2.3 Details of windows and doors: The main doors and windows (which could be opened) in the Citadel consisted of two narrow halves of the same size. They were constructed of a thick wooden frame and a network of similar sized squares and rectangular openings made from narrow strips of wood. The tops of the doors had opening filled with small glass tiles and openings at the bottom were covered with small wooden tiles. Between the top and bottom parts of the doors was a thick wooden part. All openings in the windows were covered with small glass tiles. This information helped us to imagine the shapes of a broken window or door. Figure 7 shows a completed 3D model of a door in a House of Sistani that we made by analyzing the one side of it that survived. Moreover, the remains of a broken window and the measurements of the opening in wall helped us complete a 3D model.

Figure 7. Left: Part of two side doors in House of Sistani
Right: 3D model of door and windows

Detail of facades: There is a close relationship between the interior spaces and the exterior facades. In many facades of the Citadel, we can see how the constructional elements such as arches, vaults, columns, and floor that make up the outer shape of a space reflect the inner shape. In Figure 8, the interior space and the façade have the same arch at the top of the door and windows, and the same columns on either side. The shape of a destroyed facade can be inferred from the shape of the interior elements. The problem is more complicated if interior space was also destroyed. In such case at first, we can try to ascertain the shape of the roof, walls, and other interior elements from heterogeneous data or by using analytic interpretation of relics based on construction method and then reflecting the interior elements on façade.

Figure 8. 3D model of a façade and interior space in House of Sistani

It is necessary to know the hierarchy for the positions of surfaces that make up the façade; the surfaces the main structural elements and the secondary and other layers are ranked from outer surface to inner.

4.3 Renovation

The buildings of the Citadel underwent renovations in different periods. Although we might expect that each renovation kept the character and shape of a building without change, we in fact see small changes from period to period. For this reason, we decided to base the 3D models on the shapes of buildings after the last renovation. Therefore, the heterogeneous data dating from the last renovation was the most important. The hugeness of Citadel meant that the buildings underwent final renovations at different times, and there were different groups of renovations. Each renovation period and renovation group had characteristic details. These similarities helped us to guess the details of destroyed parts from the details of the surviving parts. For example, chalk bands lining the edges of walls, niches, doorways, and arches, similar shape of ceiling in rooms, or network of mud bricks as parapet.

Figure 9. Left: Ceiling of a room in the Governor's House
Right: 3D model of another room in the Governor's House

Figure 9 shows a ceiling of a room in the Governor's House. We took the shape of this ceiling from another room in this house. This room was completely destroyed in the earthquake but the other room was left relatively undamaged and had been renovated.

5. LAYER MANAGEMENT OF 3D DRAWINGS

As mentioned above, the second phase of the 3DCG modelling developed 3D drawings to be used for 3D modelling. The 3D models had to be of good quality for public demonstrations and had to have good precision. For this reason, we tried to make the models as similar as possible to the original buildings. We also used a special set of layer names for managing the lines in the 3D drawings that define the resources. After importing the 3D drawing to 3ds Max®, the layer names of the lines were passed on to the surfaces. This layer-type management based on heterogeneous data and our interpretation of relics made it easier for experts to verify the correctness of the 3D reconstruction. Figure 10 shows an example of layer management in the 3D drawing of the governor's section. The different layers are specified by various colours. The 3D model created from the wire frame is also managed in layers like these.

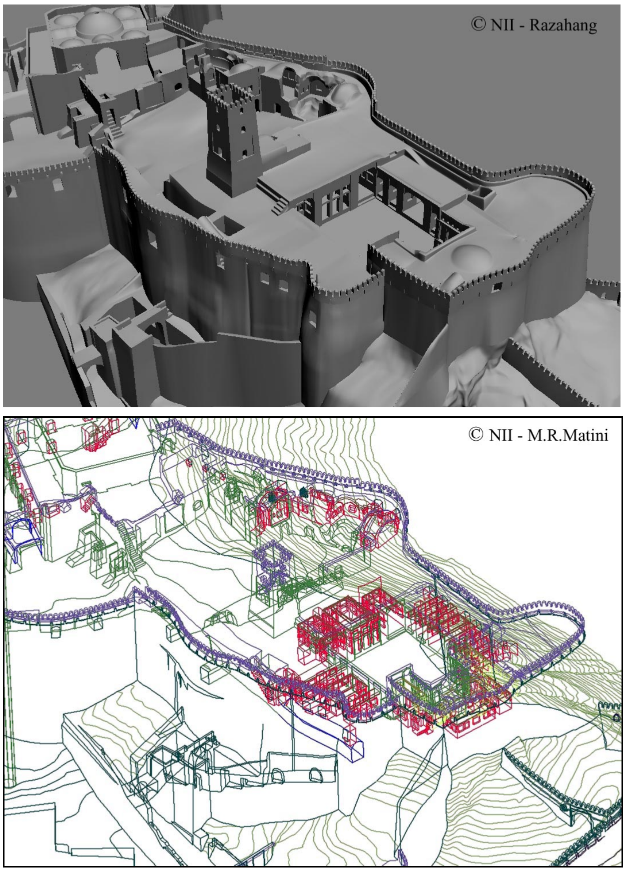

Figure 10. Top: 3D model of governor's section
Bottom: 3D drawing of governor's section with colour coding of layers with different resources

6. CONCLUSION

In making the 3DCG reconstruction of Bam Citadel, we tried to model buildings, spaces, and other architectural elements to reflect their situation just before the earthquake. For this purpose, we used heterogeneous data created before the earthquake as the main resource for the 3D modelling. Ambiguous and missing information on some of the spaces and elements were a significant problem. To complete the 3D models, we documented the relics after the quake and used them directly and indirectly. We could directly use the relics that weren't destroyed in the earthquake. The indirect use of relics that survived the quake is the main focus of this article. The relics offered valuable information for reconstructing the destroyed parts. That is, we could infer the shape of a space before the destruction. Our inferences and interpretations were based on symmetry, construction method and renovation period. We divided the lines of 3D drawings and the surfaces of the 3D models into layers based on the data used to create them in order to give experts a chance to assess the fidelity of the 3DCG reconstruction.

This case study described how relics remaining after an earthquake could be used to make a digital reconstruction of a destroyed heritage. Our work has been very much a detective investigation assembling small pieces of evidence into a whole 3D image or model. Small signs have led us to important information about destroyed parts of buildings. We devised a way making interpretations based on surviving relics. This analytic interpretation of relics can be used to make 3D revivals of other heritages that have been destroyed in natural or manmade disasters.

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