Chapter 12

Post Disaster Virtual Revival: 3D CG Manual Reconstruction of a World Heritage Site in Danger

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Additional information is available at the end of the chapter

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1. Introduction

Cultural heritage is an irreplaceable witness of the traditions and developments of the past. They are evidence of the history of various civilizations around the world. The ICOMOS Venice Charter stated (International Council on Monuments and Sites, [ICOMOS], 1964):

> "People are becoming more and more conscious of the unity of human values and regard ancient monuments as a common heritage. The common responsibility to safeguard them for future generations is recognized. It is our duty to hand them on in the full richness of their authenticity."

Modern technologies have caused several changes in lifestyles. Traditional functions have been replaced by new ones and monuments such as caravanserais, houses, and ancient castles have lost their original use. New infrastructures that are the fundamental basis for recent developments have posed numerous risks to heritage monuments and sites. Several natural or human disasters such as earthquakes, tsunamis, wars, and urban or industrial development have damaged physical bodies or the authenticity of heritage buildings. As Ben Kacyra (who established the CyArk to cyber archive heritage buildings through a 3D laser scanning system) stated (Kacyra, 2011):

> "We are losing the sites and the sorties faster than we can physically restore them. It is apparent that we are fighting a losing battle. Basically we are losing our sites and the stories as a significant piece of our collective memories. Imagine us as a human race not knowing where we came from."

There are at the moment 35 properties in the list of the world heritage sites that that have been identified as sites in danger that need specific attention and protection. For example changes in climate, erosion, and abandonment damaged the Rice Terraces of the Philippines Cordilleras. The development of agriculture around the archaeological site of Abu Mena in Egypt increased the level of the water table, softened the clay soil, and risked the collapse of buildings. The Bamiyan Valley and its heritage have suffered abandonment, military action, and dynamite explosions. Bam and its cultural landscape were destroyed by a strong earthquake in 2003 in our case study (United Nations Educational Scientific and Cultural Organization [UNESCO], World Heritage Centre [WHC], 2004).

However, new opportunities to preserve heritage buildings have been created in recent decades. Digital technologies such as 3 Dimensional Computer Graphics and Virtual Reality, Close Range Photogrammetry, and 3D Laser Scanning Systems have made it possible to make highly accurate digital replicas of heritage buildings. The Internet has provided an environment to disseminate data on digitally resituated heritage to end users. Digital tools are a key to saving heritage buildings and preserve them virtually. They can enrich our knowledge about the past and transfer this to future generations.

We introduce our research on 3 Dimensional Computer Graphics manual reconstruction of a world heritage site in danger, i.e., the citadel of Bam, as an example of post-disaster virtual revival in this chapter. A devastating earthquake destroyed the city of Bam and its rich heritage in 2003. Ten thousand lives were lost and an ancient mud-brick citadel with a unique combination of different types of Persian architecture was converted into debris. The citadel and other significant heritage of the city consisting of its urban landscape and specifically the Qanat water management system was inscribed on the list of world heritage sites in danger as 'Bam and its Cultural Landscape" in 2004 (UNESCO, WHC, 2004).

3D CG reconstitution of the citadel of Bam began right after the earthquake in December 2003. We joined post-disaster endeavours for virtual revival of the destroyed city's heritage using digital technologies as part of the Digital Silk Roads Project of the National Institute of Informatics, in collaboration with organizations and universities including the Iranian Cultural Heritage, Handicraft, and Tourism Organization (ICHHTO), Waseda University (Japan), the University of Tehran, the Razahang Architectural Firm (Iran), and the Espace Virtuel de Conception en Architecture et Urbaine (France).

The high-precision process of 3D CG reconstitution of the site faced several challenges. The citadel was vast and comprised various types of buildings and nine residential districts with a castle on top of a hill. Since most of the buildings were destroyed, precise surveying techniques such as close range photogrammetry and laser scanning could not be applied. The architectural 2D or 3D drawings and images were incomplete and several locations within the citadel had not been documented before the quake. The complicated traditional Persian adobe architecture of the buildings was difficult to comprehend, especially with the lack of reliable documentation before its destruction. Normal 3D CG surface modeling techniques could not replicate the citadel's complicated shapes of mud-brick vaulted facades and domed roofs. Our project was part of academic collaboration between universities and it involved students of architecture or CG experts from different cultures. Thus, facilitating coordination between the team members and producing a coherent 3D CG model were major challenges to be faced (Ono et al., 2008a).

Figure 1. Citadel of Bam after earthquake in 2003

We will discuss our research methods of 3D CG reconstitution of the citadel of Bam and solutions that we followed to cope with these challenges. We will introduce the key results from our research projects as a demonstration of the virtual reality of the citadel in the situation it was in before the earthquake struck and the distribution of output data accompanied by their semantics on a knowledge-based website.

2. Historical background

The citadel of Bam is part of an ancient city that is located along the Silk and Spice Road in the south east of Iran in Kerman province. The city flourished because of its textile products that were carried along the ancient routes to cities far away. The route started from the sea corridors of the Indian ocean, extended to Hurmoz port in Persia, and passed through the roads of the city of Bam to reach the east-west Silk Road.

The city was also developed for its ecological location as a basin in the middle of the desert. It gathered water through the advanced Qanat water management system that originated from distant mountains. One of the most ancient Qanats dating back to the Achaemnian period (500 B.C.) was discovered north east of the city (Adle, 2004). Several agricultural products supported the economy of the city such as cotton and dates. Travelogues such as those by Ibn Hawqal (who travelled there from 943–969 CE) described the city and its citadel (Hawqal, 1966):

> "Bam city has a pure weather and several quarters. A grand and well known citadel is located inside this city and it has three Jame mosques including a mosque inside the citadel. In Bam a beautiful, elegant and durable cotton textile is woven and is exported to lands and cities far away. The scapulars that are made in this city are very fine and made from delicate silk. Several other fine clothes are made that are sold in Khaorasan, Iraq and Egypt. Bam textile are very good quality and can be found in treasures of kings."

Such strategic locations made the city flourish during the centuries. However, the citadel inside the city has a longer history. Its original date of construction is mysterious but can be guessed from archaeological findings, resemblance of architectural styles, and even myths and stories. Discoveries after debris was removed from the citadel, such as pieces of pottery, some of which date back to the 3rd millennium B.C. (Ahmadi, 2008), and coins that belonged to the Parthian period (150 BC- 224 AD), (Armanshahr, 1993) support its origins. Archaeological findings prove the area of Bam and Baravat (south of Bam) was inhabited during the Achaemenid (550–330 BC) and Parthian (150 BC– 224 AD) periods (Ataai, et al., 2006).

The citadel is referred to in ancient myths and poems like those by Ferdowsi (Persian poet 940–1020 CE). There are stories about some parts of the citadel such as an old gate (Kod-e-Kerm) where a magical worm was kept. The worm could secrete a delicate thread (probably a silk worm) and it brought wealth and fortune to the inhabitants (Ferdowsi, 1974). There was also a deep water well that was dug by Rostam (national hero of Greater Iran) and Egyptian craftsmen in the middle of the castle of the citadel in the rocky mountains (Vaziri Kermani, 1967).

Some critical resemblance in architecture indicates the citadel might have had a more important function in ancient times. Some buildings in the governor's district, on top of the cliff of the citadel, most probably resemble an important temple in FirouzAbad (built by the Sassanid dynasty (226–651 AD)). Similar elements are the fire tower, (watch tower for the citadel), the four vaults (Chartaghi) that held fire (Four Seasons or the ChaharFasl monument of the citadel), and water resources, like springs or water wells, that were dug inside rock because ancient Persians believed that Nahid or the Water Goddess was born from stone, (deep water well in the governor's district of the citadel near the governor's bath), (Nourbakhsh, 1974).

Newer layers were destroyed after the earthquake and older mud-brick structures became evident with large mud bricks similar to those used in ancient constructions from the Elamit period (3200 BC–539 BC) (Mehryar, 2004).

The citadel has witnessed several historical events, flourishing civilizations, or destructive inventions during the last 20 centuries. When the city of Bam was an important industrial, agricultural, and trade centre in the middle of Persia in the 10^{th} century, it accommodated vast houses with huge mud brick walls (Tayari, 2005). However, its defensive function threatened its existence during insecurity in the region. In a fight with Arsalan Seljuk and his army in 1183 AD, the citadel was mostly destroyed; they diverted water from a river and filled the moat and destroyed the city's walls. After this event, and during the invasion by Ghoz into Kerman, the region was mostly destroyed, especially the Qanat systems (Aasefi Heravi, 1964), which weakened the economy of the city. The inhabitants who remained after the vast destruction in the bigger city entered the walls of the present day citadel and the large citadel shrank to its contemporary size. They replaced the large buildings and rich districts with smaller everyday houses. This event appears to have happened in 1409 AD on the order of the Teimorid governor of the city (Tayari, 2005).

However, major reconstruction of the citadel occurred during the Qajar period (1785 to 1925 CE), while the area flourished again for its date gardens. The citadel's life as a city ended in the middle of this period, when its inhabitants deserted it and created the new city of Bam south of the citadel. At the beginning of the current century, it accommodated minor military forces and finally it was registered on the National Heritage of Iran list in 1966. Although the citadel was destroyed and rebuilt several times during the last 20 centuries of habitation, no power was greater than nature, which changed the great heritage site into debris in 12 seconds.

3. Features of 3D CG reconstitution

We investigated the architectural characteristics of the buildings inside the citadel to reconstitute the citadel of Bam in 3D CG. Later, we studied the level of destruction of each case of the buildings after the earthquake. We studied different tools that were available, methods, and experience in parallel, specifically those introduced by the International Scientific Committee for Documentation of Cultural Heritage (CIPA) to choose an appropriate digital technique for reconstitution. We introduce the process that resulted in 3D CG manual modeling of major architecture of the citadel in this section.

3.1. Multi-technique approach to 3D CG development

Knowledge-based records of heritage buildings need to virtually replicate every point of their surfaces through digital techniques. Existing systems for buildings such as close range photogrammetry or laser scanning can produce points of clouds and create precise surfaces of buildings. Examples of best practices are heritage sites such as ancient Merv (Turkmenistan), Angkor (Cambodia), and Rapa Nui (Easter Island), which have been digitized by the CyArk non-profit organization. The points of cloud data and surface models of these sites, together with 28 other sites have been disseminated over the Internet.

However, these processes pose greater challenges for heritage in danger that has partially or completely been destroyed. The original shapes of buildings cannot be laser scanned as they do not exist anymore. If sites have been photographed with calibrated cameras before destruction, then CRP can help to extract points of surfaces. The three metric images acquired in Bamiyan in 1970 by Professor Kostka could be used to reconstruct the Bamian Great Buddha with VirtuoZo digital photogrammetric systems (Grün et al., 2004).

Unfortunately, such metric on-site images were not available for the citadel of Bam. Yet an aerial photograph of the citadel in 1994 was available, which could be used for cartography to generate a 3D drawing with remote sensing techniques. Although such systems can be used to extract the major dimensions and geometry needed for the heights and plans of buildings, they have shortcomings in elevation and interior spaces.

Manual 3D CG modeling was a traditional but effective method in our case study by enabling the geometry of surfaces from 2D architectural drawings to be created. Tools such as Auto CAD ® provide a metric environment for precise modeling specially with lines, such as the borders of arches and the edges of walls. 3DS MAX ® has a powerful interface for generating curves and free-form surfaces such as the mud-brick constructions of the citadel.

The site was surveyed before the earthquake and 2D architectural drawings as plans, section facades, and perspectives were available (Iranian Cultural Heritage, Handicraft and Tourism Organization materials). Several onsite photos were also available to help disambiguate interior spaces.

Therefore, we chose a multi-technique approach for 3D CG reconstitution. We exploited a 3-D photogrammetric map (which was made available to us under the Irano-French 3-D Cartographic Agreement on Bam (IFCA) and the Iranian National Cartographic Centre (NCC)) that had been reconstituted by Prof. Adle and his team from aerial photos of the citadel of Bam from 1994, as a basic resource to provide planar dimensions. We later used 2D drawings and photographs to complete a 3D model of the buildings both from the interior and exterior (Ono et al., 2008 b).

Our main decision was to find suitable case studies and to choose manual or automatic techniques of 3D CG modeling. Manual 3D CG modeling of destroyed buildings with the high degree of precision and the multi-technique approach we previously discussed is a time consuming and difficult task and needs accurate basic documents. Consequently, we needed to select the buildings carefully according to their architectural features.

3.2. Architecture of the citadel

We had to study the citadel’s architectural style carefully to create a 3D CG reconstitution of it. The citadel was divided into three important sections of a district for the public and general inhabitants, an area for military buildings and residences, and the governor's district. These districts had different levels with different heights (of around 50 meters). There were various types of buildings in each district that were partly damaged or totally ruined after the earthquake.

The major architectural features of the citadel can be divided into six parts:

1. Surrounding Walls

There are five defensive walls that surround different sections of the citadel. The first and longest wall with an approximate length of 2000 meters embeds the whole citadel. The second wall separates the military and governor's district from the areas for the public. More than 40 watch towers divide the surrounding walls into shorter sections. There are embankments at both sides of the wall to strengthen its defensive functions. A moat was dug at the outer side of the wall to fortify the city.

The third, fourth, and fifth wall successively surround the governor's castle and were built in different centuries.

Figure 2. Architecture of citadel of Bam and its different types of buildings. Photographic credits: ICHHTO (top left, center, bottom center, and right) and NCC (top right and bottom left)

2. Gates (Entrances)

The citadel has only one main entrance gate that is located at the south side of the first defensive wall. This entrance has an octagonal small yard that is strongly fortified by watch towers. The second gate is located on the south side of the second defensive wall. A winding narrow path starts from the second gate, goes through the military buildings, and ends at the governor's castle. There are two old gates belonging to earlier centuries of the citadel that were closed by later defensive walls. The gates of the citadel are made of a vestibule that is protected by two adjacent defensive towers and guard rooms watching over the entrances.

3. General Populace Districts

There are nine districts in the citadel that were inhabited by ordinary people. These districts consist of one or more large complexes of houses and several other small ones that are separated by narrow streets. The houses are closed to the outside so mud-brick walls with entrances to houses can only be seen in the streets. Most of the large houses were restored before the quake and have an important architectural style for courtyard houses in the desert. However, the small houses are partly ruined and eroded and do not have distinguishable architectural forms. The borders of small houses are hardly visible and their shapes are vague. Before the earthquake they were not restored and left in ruins.

4. General Buildings

General buildings of the citadel that are used by the public are common to other types of Persian architecture. A bazaar starts from the main gate and divides the general populace district of the citadel into two sections. A mosque is located near the most important quarter of the citadel. A Madrasa or school and residences for pupils are located in front of the mosque. A ceremonial building with a large plaza called Tekiyeh is located beside the bazaar. Some caravanserais are located adjacent to the public buildings to accommodate outside travellers. These buildings were restored before the earthquake and have characteristic architectural features.

5. Military Buildings

The military facilities are located right after the second gate and defensive wall of the citadel. There is a stable that once had the capacity to house 200 horses with dwellings for superior officers. The military facilities also have barracks and a water well, a house for the commander, and a wind mill. They are a well-designed combination on the lower slope of the hill of the citadel.

6. Governor's District

This section has the most important monumental buildings of the citadel. There is a house for the governor with a spacious courtyard and vast Iwans overlook the whole city from the top of the hill. There is also a high square watch tower, the governor’s bath, and a deep water well. The most important symbolic building is located on top of the citadel. It is a monument called the Four Seasons and it has a room with four archaic doorways facing north, south, east, and west. The governor could welcome his guests in this building and could show them the whole city in the south, the mountains in the north, and the palm gardens in the east and west. It might have had a regional purpose with such a unique architecture and spectacular views (as was mentioned in Section 1) in earlier periods.

3.3. Types of 3D CG modeling

According to our survey on the architectural characteristics of the citadel, the situation with the buildings after the quake struck, and the available material, we divided the citadel into three parts.

1. Less Important Areas

The general populace districts, which were the largest of the three areas, did not have a specific architectural form (as explained in Section 3.2 (3)) and the main documentation for them was in the form of aerial photographs. No precise 2D drawings were available and the 3D photogrammetric map could not be directly used to distinguish the architecture of the buildings. Therefore, manual 3D CG modeling of the site was not an appropriate method. A semi-automatic process with the help of a 3D photogrammetric map was tested simply an elevated plan and create areas filled with images of the district before the earthquake struck.

2. Moderately Important Areas

The surrounding walls of the citadel (as explained in Section 3.2 (1)) were the longest of the three areas; their documentation was similar to that of the less important areas but their architectural form could be better recognized. Manual 3D CG reconstruction of the wall was time consuming and unnecessary. Therefore, automatic 3D modeling was tested by giving volume to different sections of the wall along specific paths.

3. Very Important Areas

The general buildings, military buildings, and the governor's district (as explained in section 3.2 (2), (4), (5), (6)) were combined together in a complicated way over the slope and the hill of the citadel. Documentation for these buildings was available. Removing debris made it possible to measure their remaining walls, foundations, and vaults and assist the documents.

3D CG manual modeling of the buildings in this category was started in two major phases of research, from 2005 to 2007 and 2007 to the present, which will be discussed in the next section (Matini et al., 2008).

4. Manual 3D CG modeling of very important areas of the citadel

Manual 3D CG modeling of the citadel was primarily based on the documents surveyed before the earthquake. Several sources of architectural information were investigated as a first step and different types of data were collected. We prepared a manual 3D CG model of the most important buildings from 2005 to 2007 by directly applying heterogeneous data. We improved our method based on this experience and completed the 3D CG model of all very important areas of the citadel by using a CAD-based 3D drawing as a basic resource for 3D CG modeling. We will explain the processes and discuss their shortcomings in this section.

4.1. Heterogeneous data collection

We provided a database of heterogeneous information as a basic document for 3D CG restitution of the citadel. Although 2D architectural drawings of some of the buildings' plans, sections, and facades were available, they were not precise. Due to the irregular shapes of the mud-brick structures and application of traditional methods of construction such as arch-and-vaults or domes, the surveyed drawings had errors or contained insufficient information. Therefore, we investigated other resources, specifically images. Immediately after the earthquake struck, we made a call for participation over the Internet and collected several photographs of the citadel taken by tourists from around the world on our website (http://dsr.nii.ac.jp/bam/index.html.en). The photo-database was completed with resources provided by organizations such as ICHHTO, NCC, and NHK. These resources included onsite, satellite, and aerial photographs. However, the photos were mostly low resolution, too many of them were of popular views, and very few images were of private buildings or residential districts. There was also a lack of images of interior spaces, no data were related to settings on cameras, and no photos were available from metric cameras.

Aerial photos were complementary data for creating the 3-D models, which were taken over seven different years (the first dating from 50 years ago), and those with a scale of more than 1: 2000 were provided by the National Cartography Centre and Digital Globe. These photos revealed the changing situation with the citadel during the last 50 years. In fact, we recognized three different periods before 1971 in which the citadel had been abandoned and suffered damage from nearby human habitation; the citadel was partially restored from 1971 to 1993. The citadel underwent massive reconstruction as one of five large ICHTO projects from 1993 to 2003.

We decided to reconstitute the citadel virtually to the physical form it had right before the earthquake struck in 2003.

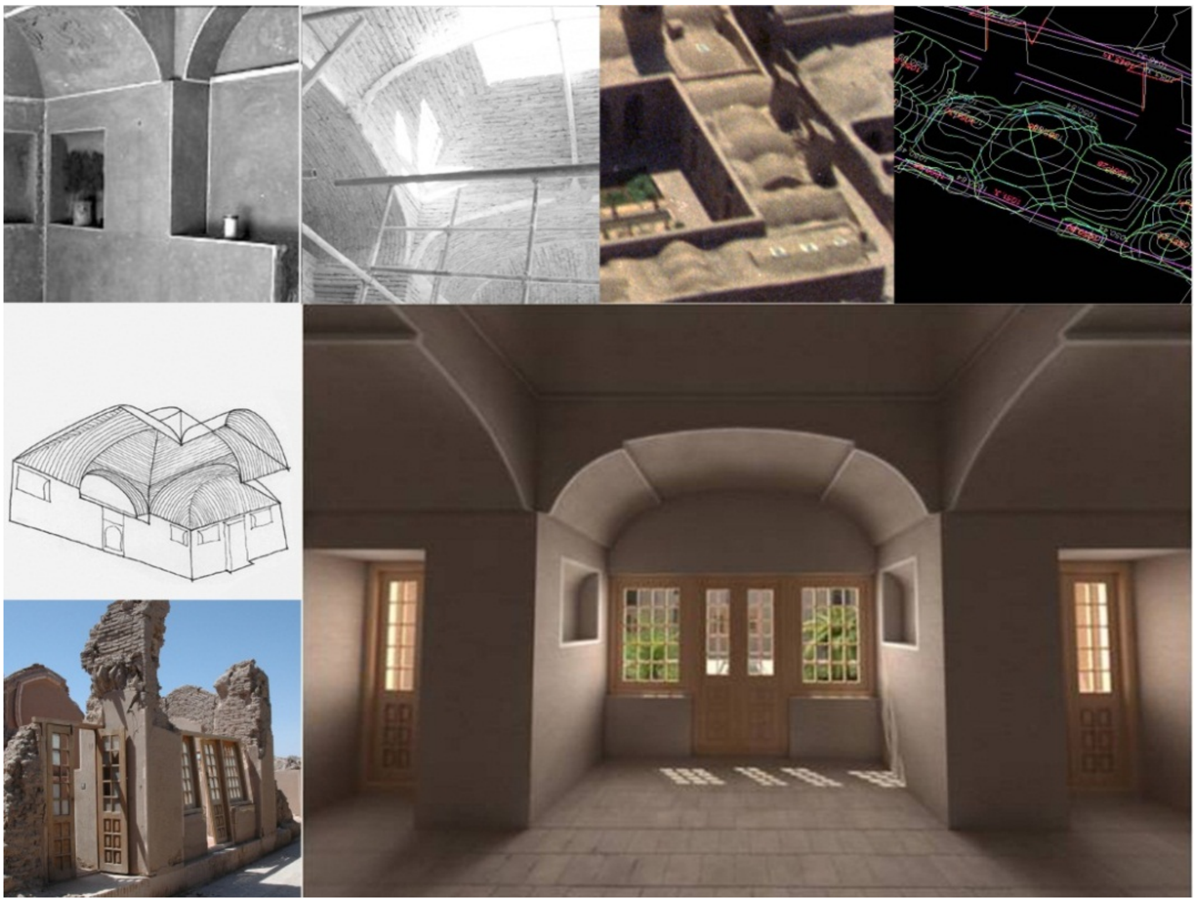

Figure 3. Heterogeneous data are needed for 3D CG reconstruction of citadel of Bam.

On-site images (top: 1st and 2nd from left), aerial photo (top: 3rd from left), 3D photogrammetric map (top: 1st from right), sketch (middle: 1st from left), on-site image after quake (bottom: 1st from left), 3D CG rendered image (bottom: 1st from right).

We made several sketches of different spaces within the citadel to find the original shapes of missing spaces such as interiors or details after questioning experts who had worked there before the earthquake struck, especially about the shapes of vaulted ceilings and roofs. This method was practical specifically for interior spaces with no records of documentation (as shown for 3D of ceiling of the north middle room of Sistani House, big yard in figure 3).

One major document was 3D photogrammetric restitution of the citadel (IFCA project) using aerial photos of the citadel dating back to 1994. The 3D photogrammetric map helped us to correct errors in 2D architectural drawings, to ascertain building heights and dome shapes, and specifically to locate every building at the site by using a *Universal Transverse Mercator* (UTM) system (Ono et al., 2008b).

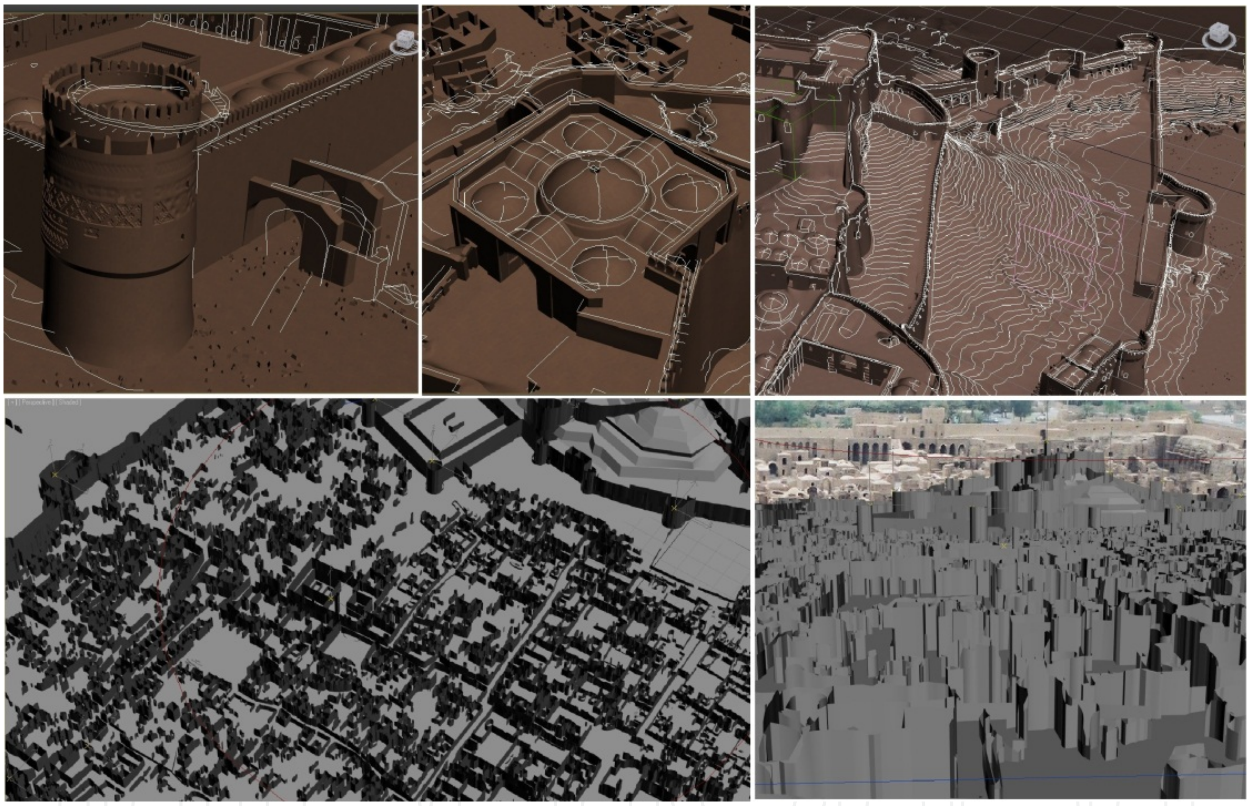

Figure 4. Application of 3D photogrammetric map (IFCA project of prof. Adle and NCC) for adjustment of 3D model (top: 1st from left), adjustment of height of tower of stable, white lines are 3D photogrammetric map. (top: 2rd from left), extraction of counter lines of the domes of roof of Four season monument, (top: 1st from right), adjustment of shape of slopes of the hill from topographic lines (bottom: 1st and 2nd), adjustment and extrude of counter lines of ordinary houses.

We watched every available video of the citadel in parallel with the map and took snapshots from the videos and processed the extracted images specifically to reduce contrast and darkness, and we used the images to disambiguate details of interiors or decorations as no photos were available. We studied different textual resources about the history and architecture of the citadel of Bam to support semantic annotations of the buildings, and to support conceptual representations of 3D CG modeling.

4.2. 3D CG modeling by direct application of heterogeneous data

3D CG modeling was started by using two buildings featured at the citadel: the main gate and the Four Seasons monument (by the Waseda University team). Five major public buildings, each of a different type were added to the work (by the University of Tehran and Razahang teams). Teams of 3D CG modelers simultaneously used different types of data for the first phase of manual 3D modeling. However, the lack of precise 2D drawings for many of the citadel's buildings made it necessary to use heterogeneous data directly in 3D CG modeling. Such data can help the team to find more information about the spaces to be modeled, but it is not always easy to use.

The CG modelers used the heterogeneous data by themselves to model the seven buildings in 3D. They followed a two-step process:

4. They superimposed the 2D drawings onto the 3D photogrammetric map, corrected the dimensions of the plans, adjusted the heights, and completed details such as the shapes of domes on the roof (which were precise in the 3D photogrammetric map)
5. They extracted several missing details on the facades and interior spaces by acquiring the geometry and proportions from on-site or aerial photos and corrected the 3D models.

This process required high levels of expertise in both architecture and 3D modeling. Applying the two types of data simultaneously led to confusion regarding domain knowledge on the part of the CG modelers, because they were not familiar with traditional Persian architecture.

To ensure the resulting 3D models were precise, we checked carefully the models provided in this stage.

4.2.1. Systematic 3D CG modeling in different layers

A layer management strategy was proposed to name each component of a 3D model on the basis of the component's type, its location, and the resources used for 3D modeling. We devised a simple methodology similar to morphology by defining affixes to name different layers as a single string. A prefix was designed to indicate the type of building. An infix specified the data type that was used for 3D modeling such as architectural maps (plans, façades, and sections), 3D photogrammetric maps, photos, movies, and sketches. A suffix was defined to show a building component or an architectural element and its location as an interior or exterior part.

The layer manager in MAX® is a function for organizing and managing objects in complex scenes. Each layer has some attributes such as colour. Semantic layer management of the 3D models of the citadel of Bam provided a systematic model with several advantages. The supervising team could turn the layers on or off and analyze the components of the 3-D model, or it could make one or more layers transparent (by changing the 'opacity' of the component in the 'material editor' function of MAX®) and check the correctness of the rear of the target component. As each layer could have a different colour, it was easy to recognize when the components of the 3-D model interfered with one another. The user could also search inside the 3-D models to retrieve specific components according to the layer management metadata.

The most important advantage of layer management is during the process of merging individual 3D models into a unified one. Our final output to reconstruct very important areas with 3D CG consisted of at least 25 models that were prepared by different teams. The 3D CG modeling tool had default-layer naming and if a layer-naming system had not been implemented, the components of the models would have had similar layer names and errors would have occurred. We merged the 3D models with correct coordinates of the UTM system for each building without error on a ground surface model extracted from a 3D photogrammetric map with this method (Ono et al., 2008b).

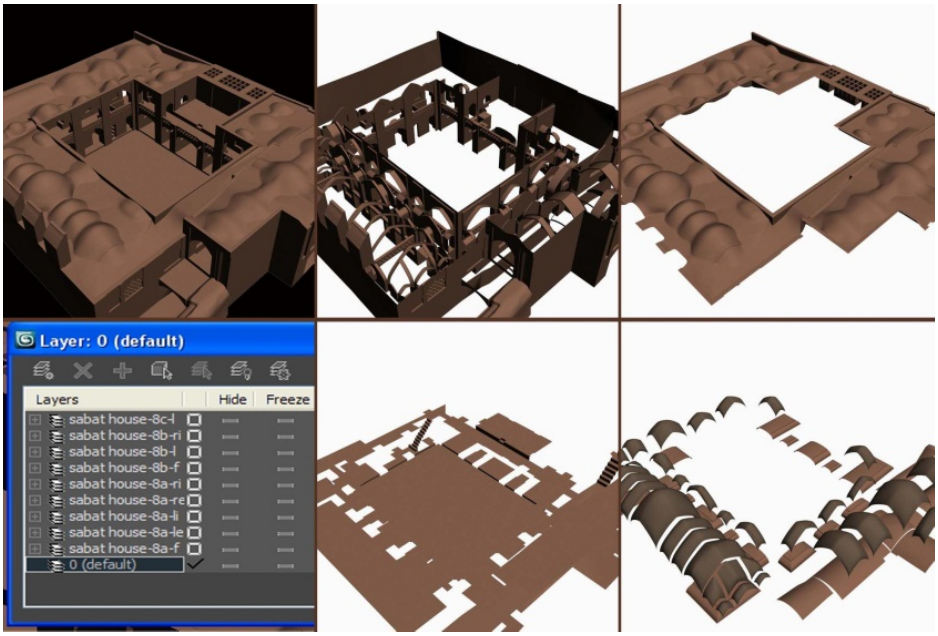

Figure 5. Implementation of layer management system for 3D model of Four Seasons monument

4.2.2. Quality control of 3D CG models

Quality control on the 3D models was carried out to ensure the 3D reconstruction process was correct. The scale of 3Ds was unified and the geometric coordinates of the elements and their correct positions within the citadel as a whole were specified. The initial 3D models that were developed by the team of CG experts were evaluated to identify incomplete parts or components with errors. The interior spaces, vaulted ceilings, or ornaments had problems due to a lack of accurate 2D drawings. Therefore, the architecture for the 3D models was controlled by analytically interpreting relics using the heterogeneous resources in the following categories:

6. Architectural
a. Superimposition of different architectural drawings

We superimposed plans of different levels of selected buildings, facades, and sections, and compared them with 3D models. Displacements were found that confused the modelers about the dimensions of walls on the ground and first floor, the alignment of load-bearing walls over each other at different levels, and the heights of towers. We merged 3D models with a 3D photogrammetric map based on some reference points. The correct measurements of heights and exterior borders of buildings were marked and reported.

b. Comparison with photos, sketches based on oral explanations by experts, and videos

The complicated architecture of the citadel had missing details in the 2D drawings. The exact shapes of arches, details on decorations, and correct forms for the domed surfaces of roofs were major errors in the 3D models. Photos had to be used to disambiguate the details. We tried to extract as much information as possible from the photos using scalable components such as human scale. We made a library of traditional Persian arches common to the architecture of the citadel and gave the 3D modelers drawing instructions.

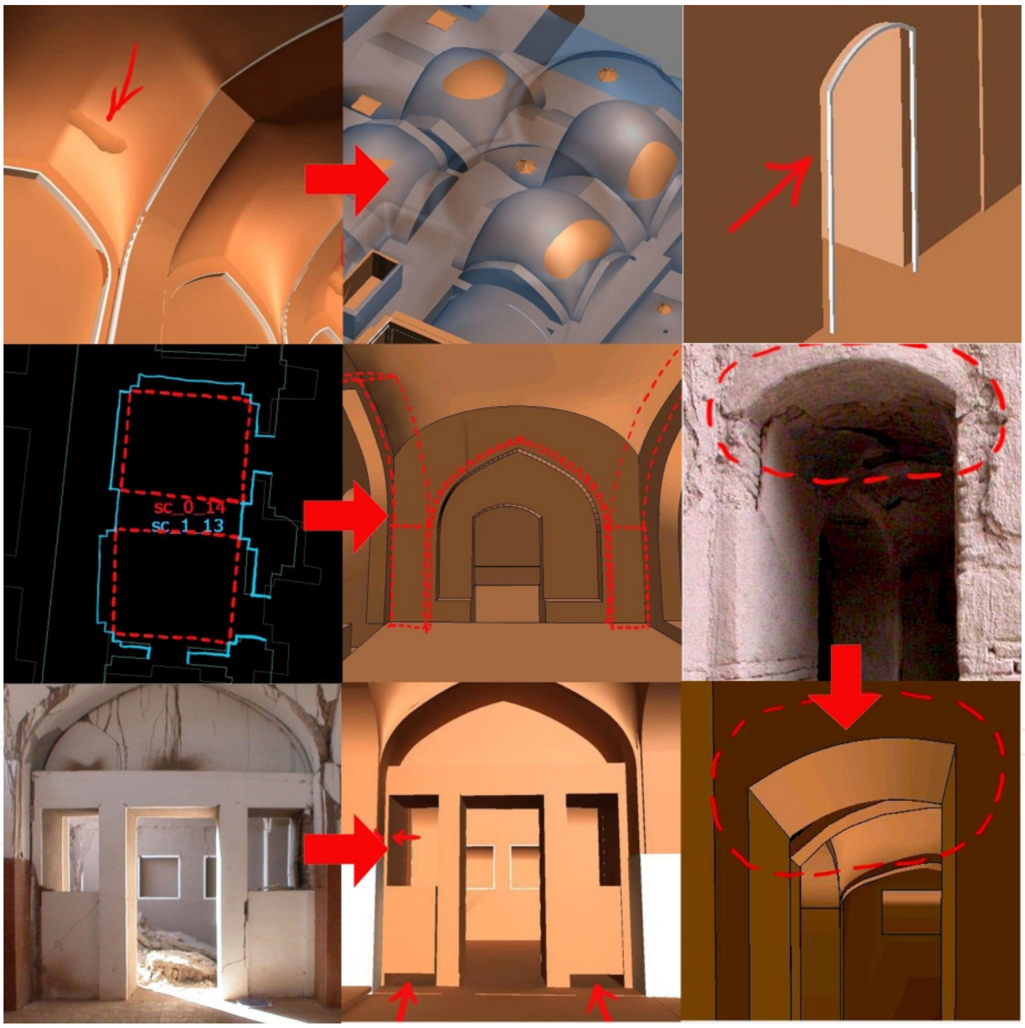

Figure 6. Errors in technical 3D CG models during first phase of project

c. Comparison with similar styles of construction

Of the different components of 3D models, the interior spaces of less well known buildings had the least basic information and contained errors. We tried to compare the geometry of the spaces with other similar spaces inside the citadel or inside the city of Bam and found similar styles. This method was specifically useful for interior vaults. The aerial photos were helpful to deduce the locations of walls and styles of coverings. Specific instructions were provided for modeling and reporting the most well-known vaults in the citadel. The instructions included simple models of the details of ornaments such as chalk bands around vaults and columns or brick-work decorations.

7. Technical 3D CG modeling
a. Selection of suitable surface modeling technique

We selected Auto CAD ® and 3ds Max ® from the different tools available for 3D CG modeling for our work. These tools have different functions and can cover different applications. AutoCAD provided a coordinated environment to draw precise lines and dimensions. Therefore, 2D drawings were first matched together to form initial 3D drawings of extruding solid surfaces of walls with this tool. However, problems started with 3D modeling of the free-form surfaces of the adobe of the citadel.

There were insufficient 3D meshes that were formed between four-sided volumes in the tool. Although newer versions (AutoCAD 2012 ®) are empowered with more sophisticated surface modeling such as *non-uniform rational basis* (NURB) splines, the 3D modeling that was started with the tools in 2005 had shortcomings for our purposes. Therefore, several initial drawings were imported from AutoCAD ® to 3ds Max ® for modeling.

As the process had errors with some surfaces, specifically the meshes of vaults, the modeling of ceilings, vaults, roofs, and details were started from scratch with the 3ds Max ® tool. The tool provided different methods of surface modeling where each was suitable for particular forms. We proposed mesh surfaces for barrel or cloister vaults that had four specific sides that were symmetric. Roofs or non-geometric surfaces of the ground were modeled by using polygons or NURBs. These two allowed a case-by-case approach to modeling to fill in all the surveyed geometries and the surfaces of arched vaults or roofs as each room of the buildings was different in its own way.

b. Selection of proper level of details

3D CG modeling of the buildings inside the citadel of Bam with a one-to-one scale of details needed every detail of one centimetre or less to be precisely reconstituted. Modeling adobe architecture with tools such as 3ds MAX ® was like digitally rebuilding a site from mud; soft and curved surfaces of mud brick needed high levels of detail of their surfaces. This made the models heavy, which will be a problem when all models are merged and rendering is carried out. We checked the size of meshes or polygon details and the geometry of intersecting solids or surfaces to optimize the level of details and avoid unnecessary large size files.

c. Control of adjacency of 3D components

Seams between components, e.g., at the joints between facades and interior spaces, interference by 3D solid parts, such as ceilings with exterior walls, chalk decorations with mud brick walls, and similar errors, were evident and checked in the 3D models. Layer management helped us to separate different components such as walls, roofs, and ceilings and check their adjacencies and report the errors (Matini, Ono, 2010).

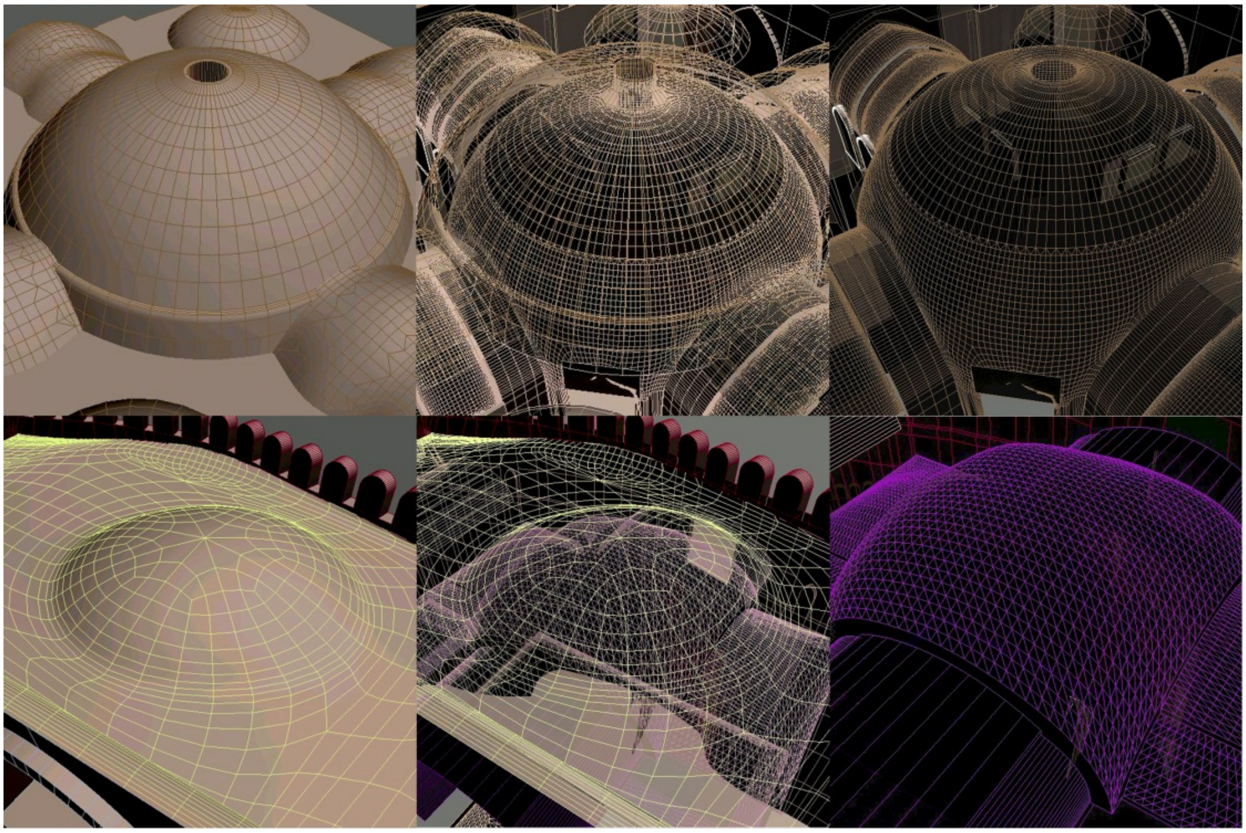

Figure 7. Different methods of surface modeling for ceiling and roofs in citadel of Bam (outer surface of roof and inner surface of ceiling below it are showed)

4.2.3. Evaluation reports

According to the quality control specified above, we took snapshots of the errors and compared them with our data by using knowledge on the geometry, proportions, structure, and scale of the adobe buildings. From 2005 to 2007, during which the first phase of 3D modeling of the seven buildings was almost completed, we evaluated the 3D models of all buildings during the development phase at least three times and identified between 100 and 200 errors (architectural and technical) each time that needed to be modified. We also provided evaluation reports to ask for corrections and also organized meetings and discussions with the modelers. Hundreds of pages of questions for evaluation were prepared and sent to different teams of CG modelers (Waseda University, Prof. Kawai's laboratory in Tokyo, the University of Tehran, Prof. Einifar's laboratory in Tehran, ENSAPVS, Prof. Bouet and Prof. Dell's laboratory of EVCAU in Paris).

The errors were carefully observed by the CG modelers and corrected. They provided answers to the corrected errors and created the final results for the first phase for the seven buildings with the best possible precision.

4.3. 3D modeling by CAD-based 3D drawings as basic resources

The correction process for the first phase of 3D modeling was complicated. Several problems resulted from the modelers' application of heterogeneous data and their corrections took a great deal of effort. Sometimes remodeling was easier than making modifications to some errors.

To solve this problem in the second phase of the project (beginning October 2007), we developed CAD-based 3D technical drawing as a unified method of basically drawing the citadel. The drawing was developed in a sequential modification process using the domain knowledge and contribution of architectural experts. They could comprehend the chronology and the original shapes of the mud-brick buildings.

First, an initial drawing for the interior spaces was developed from 2D drawings. In some cases, we surveyed the remains after the earthquake struck, but in many cases no measurable remains were available and only 2D drawings surveyed before the earthquake were used. Later, the 3D photogrammetric map was directly used as an initial drawing for exterior borders of the buildings, roofs, and heights. Initial 3D drawings were adjusted and completed through a number of different modification steps. One architectural aspect of the model was evaluated in each step and modified by applying one or more heterogeneous data items. The modifications were made sequentially rather than simultaneously to avoid confusion and the possibility of missing important features. The modifications comprised geometrical, structural, and proportional changes and the adding of details, which are discussed below.

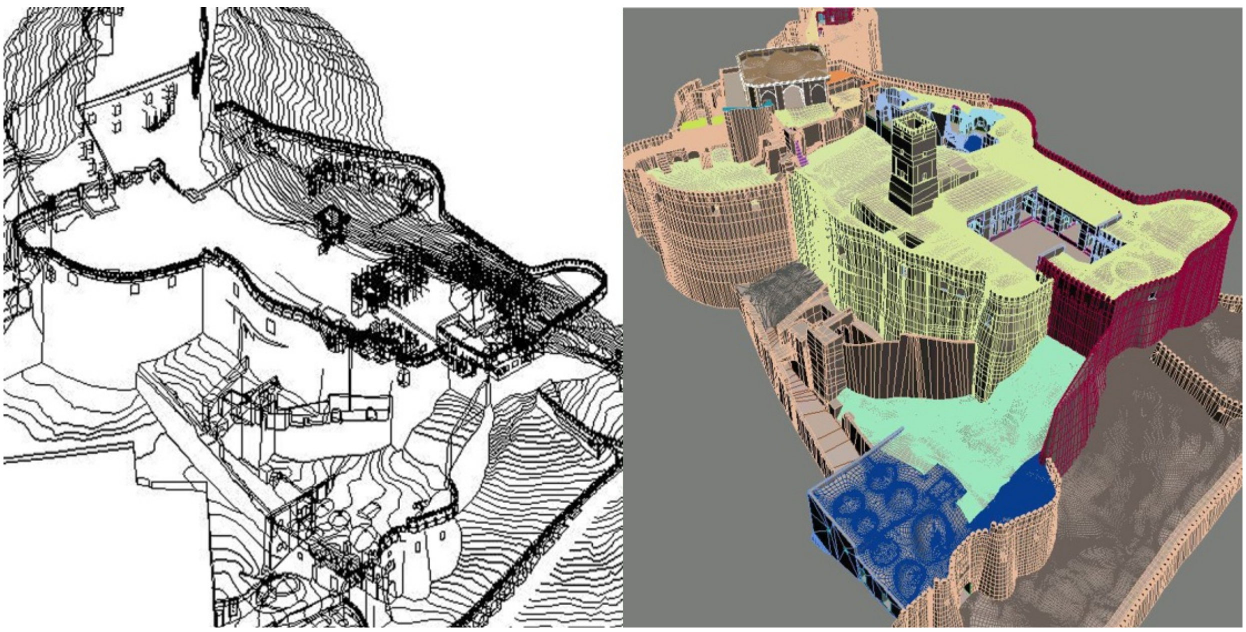

Figure 8. CAD-based 3D drawing as basic resource for 3D CG modeling of governor's section and 3D model

8. Geometrical Modifications

The incomplete parts of the 3D models that were identified during the first phase of the project were mostly from spaces without information, specifically interiors. Geometrical features of an architectural element helped us to sketch and modify these spaces.

For example, the shape of the roof visible in aerial photos can specify the geometry of an interior ceiling or location of a wall. Shadow and light visible on the floor or wall in a photo can reveal architectural elements such as windows. A symmetric space can help to mirror an available section. Similarities between components such as niches can also help to identify the shapes of missing parts of the 3D models.

9. Structural Modifications

Traditional adobe buildings have limited features of construction. Load-bearing walls are covered by specific types of roof systems such as barrel-vault, cloister-vault, or arch-vault types of covering. However, adobe has less resistance as a material than brick, and the domes or vaults might not be completely symmetric; minor changes can also be found in different centuries of construction such as the shapes of arches and the heights of domes.

The height of interior ceilings was one of the most serious problems in the drawings. Measurements based on the 2D drawings were insufficient and some ribs of ceilings reached outside the surface of the roof in the 3D models.

The outer surface of the roof was modeled in this stage by using the 3D photogrammetric map. As the domes were not symmetric, two orthogonal splines were drawn for the curvature of the domes. Therefore, the style for the roofing structure was extracted, and the thickness of the ribs or vaults was determined (around 12 cm for vaults and 32 cm for arches). Finally, the surface of the ceiling was modeled.

This process needed an on-site survey. Some vaults were not completely destroyed and could be measured after the quake. Some portions of the vaults or arches were surveyed after debris was removed from the citadel and the 3D drawings were correctly completed based on structural features.

10. Proportional Features and Details

Traditional Persian buildings have specific module of dimension that specifies their proportions. For example the span of a doorway, 103 cm, is a module that controls the proportions of rooms. Therefore heights, angles, spans, thicknesses, and other parameters were drawn in a wireframe model according to extracted proportions. Photos were primary resources to make proportional modifications. Unfortunately, we could not find a metric photo to provide a rectified image and directly take measurements from photos. However, we could use some functions of the MAX ® tool such as camera matching, and could find approximate perspectives for scenes. Then, scalable parts in scenes, such as floor tiles and the human scale could be identified and the approximate proportion of whole scenes could be extracted; as a result, the geometry of 3D drawings could be completed. This method was helpful specifically for details such as niches, columns and chalk band decorations.

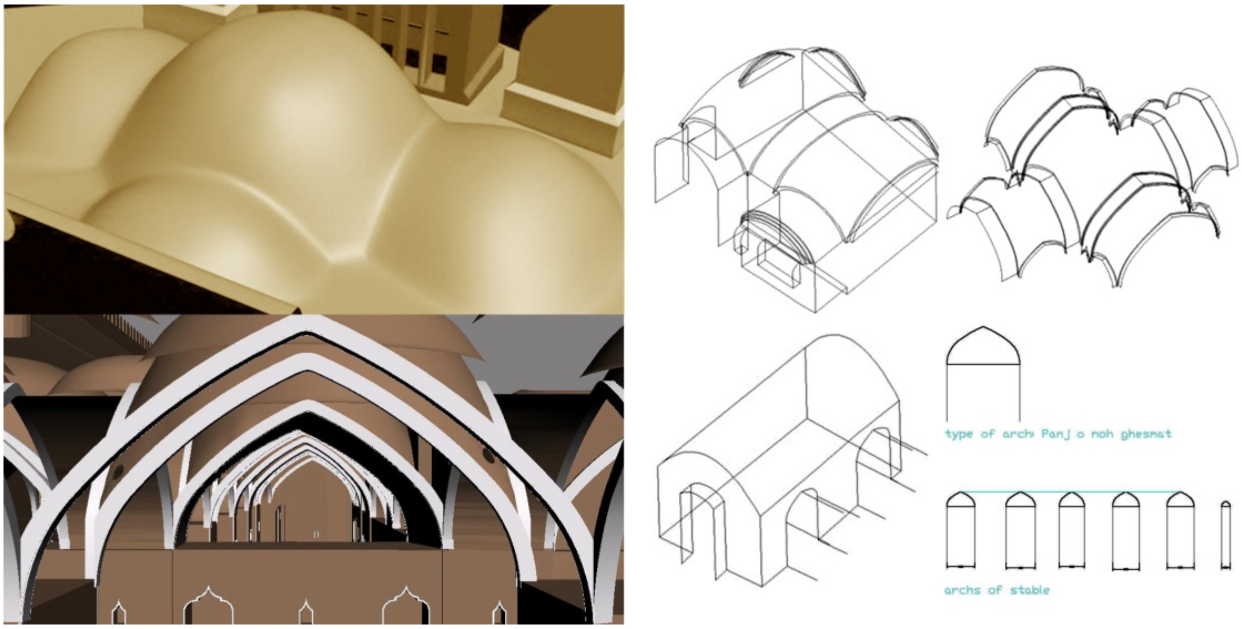

Figure 9. Geometric and structural modifications to make the wire frame of the ceiling and the roof and complete the 3D CG modeling

CAD-Based 3D drawing, which was prepared by complementary application of heterogeneous data, had detailed specifications on the architecture of the citadel. The whole governor's section, surrounding walls, second and old gates, and other complicated spaces of the citadel located on Bam's hills were completed with this method. 3D drawings were easily imported into the 3ds Max® environment and completed by 3D modelers who had little domain knowledge. They imported DWG files into 3ds Max®. Their task was only to define suitable faces between the borders of 3D drawing lines. This reduced the amount of synthesis they needed to do for the original shapes, especially for arches, vaults, domes, and the proportions of niches. In most cases, the lines were given for all details and the only challenge was to choose proper surface modeling or a proper modifier from a large number of tool options, such as polygons or NURBS for cloister vaults and meshes for barrel vaults. We used this method to finish the modeling of 20 buildings and several defensive walls of the citadel between 2007 and 2010 (Matini, et al., 2008).

5. Key results

The results for the 3D CG manual reconstruction of the citadel of Bam demonstrated that we finished 3D modeling of every building in areas of great importance that had been restored and made safe before the earthquake. For moderate or less accurate areas, we tested methods of automating the modeling process to reduce the time and cost required for reconstruction. One method that was proposed for semi-automatic modeling was to refine the photogrammetric map toward the 3D models of unimportant buildings and paste texture from tourist photographs onto the models (Kitamoto et al., 2011).

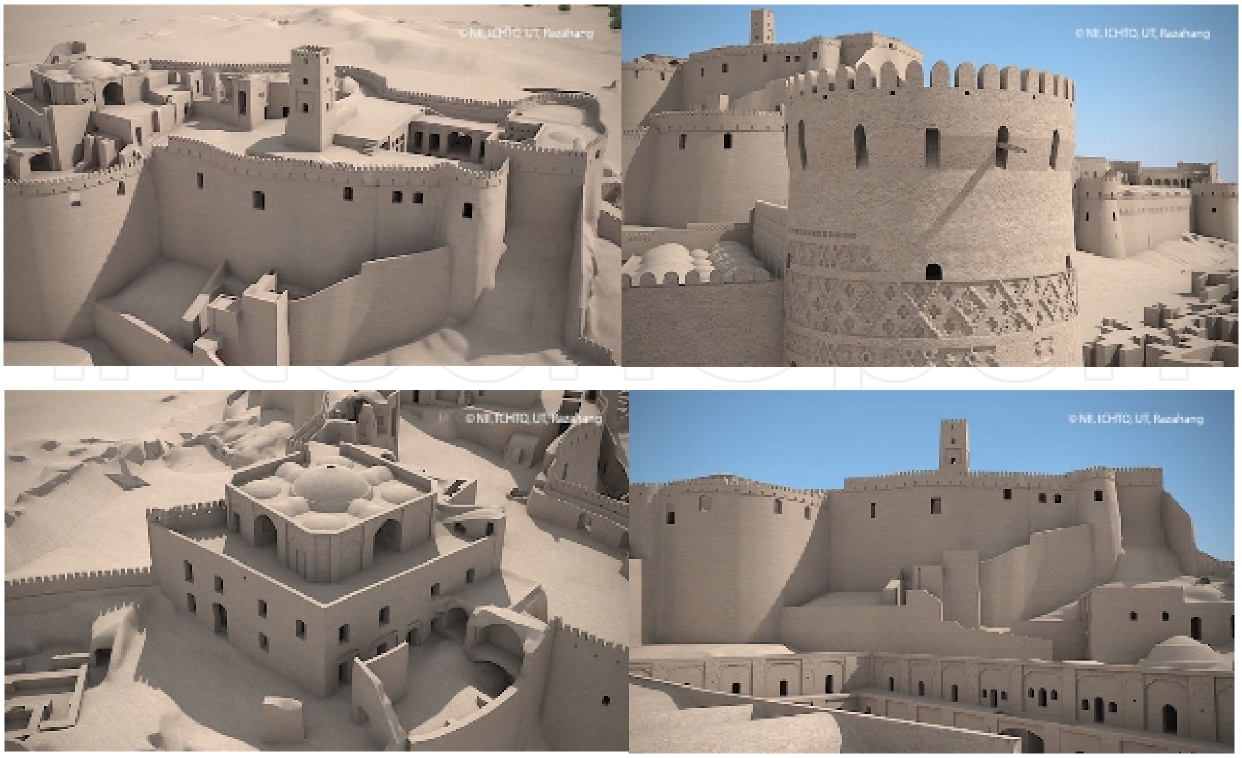

Figure 10. Results for 3D CG reconstitution of very important buildings of citadel of Bam

5.1. Bam 3D CG ontology driven website

We presented our visual output data as rendered images, Quick Time Virtual Reality (QTVR) videos, or walkthrough videos as part of the conceptual process of our project on the Bam3DCG Website (http://dsr.nii.ac.jp/Bam3DCG/). In comparison to the architectural process, conceptual modeling is about representing our knowledge of cultural heritage by defining the semantic relationship between knowledge of the domain and output data. Since we were dealing with heterogeneous data, the data needed to be explained with semantic annotations linked to various concepts associated with the data. We developed the Bam 3DCG ontology-based Website for this purpose.

To acquire the semantics of the citadel of Bam, we designed an ontology knowledge model called Bam 3D CG ontology using three major schemas: a metadata-based schema, which was conceptualized using different metadata standards, a referencing-based schema, which provided the location or bibliographic attributes such as a historical summary of each building from different travelogues or historic references), and a lexical-based schema, which provided terminological specifications for every building in the citadel.

Every piece of information, or visual output data, is an entity connected to other entities by semantic links in this ontology designed using the Protégé knowledge acquisition tool as a Resource Description Framework (RDF) file. These links are descriptive attributes of entities. Each homogeneous group of information is hierarchically categorized in classes with subclasses.

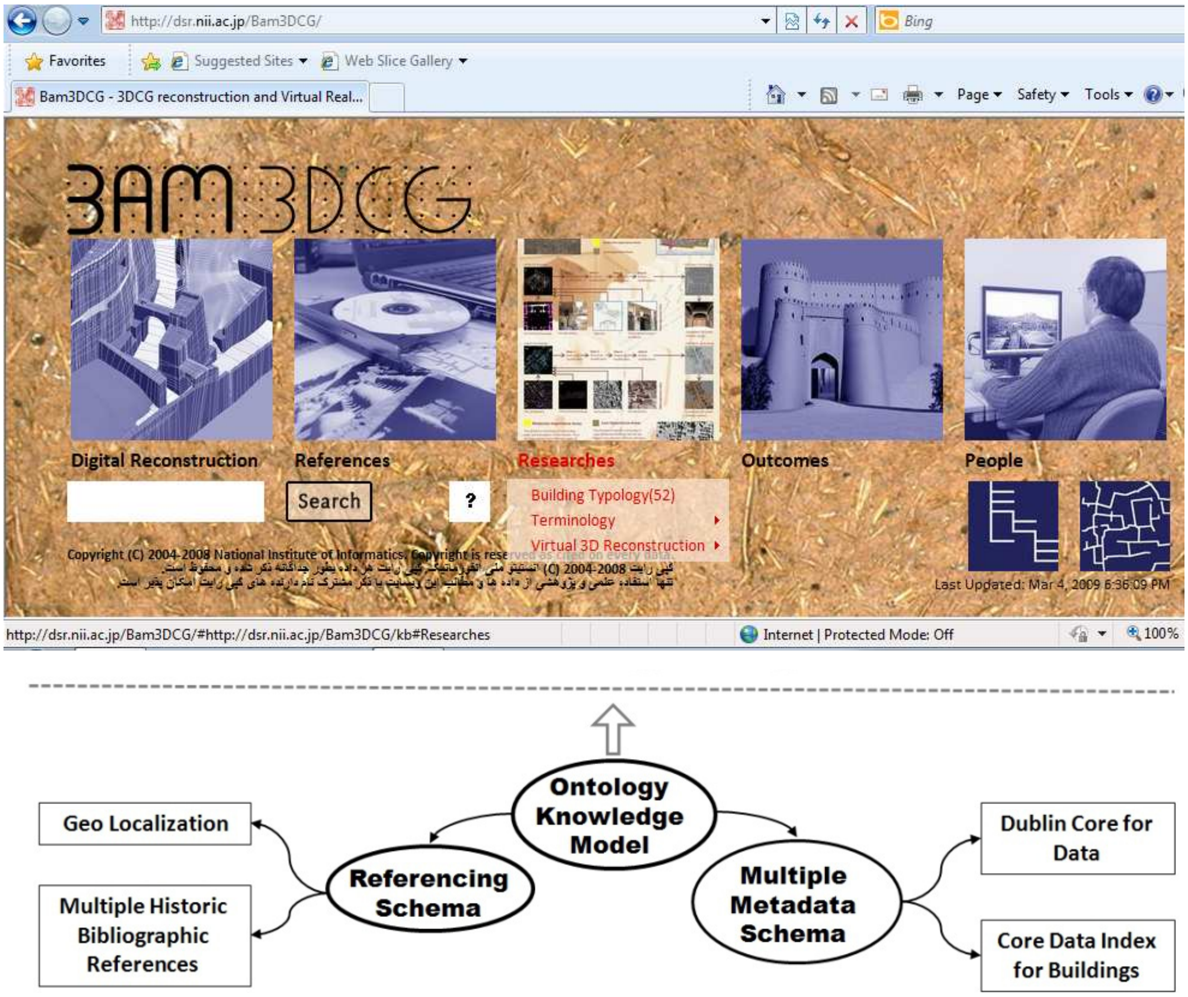

Figure 11. Architecture of Bam 3D CG ontology driven Website

We selected the Core Data Index to Historic Buildings and Monuments of the Architectural Heritage (Thornes, Bold, 1998), which was part of the Object ID standard to describe the attributes of the buildings (such as name, location, date, material, etc.). We used the Dublin Core Metadata Element Set, which is a standard vocabulary of fifteen properties for use in resource descriptions to describe and catalogue visual data that consisted of photos, videos, architectural drawings, and sketches. The multilingual lexical schema of the ontology provides the semantics of all buildings in different languages. We designed a Website generation and maintenance system to browse the RDF graph created on Protégé so that people could browse knowledge bases using a standard Web browser.

Bam 3D CG displays rendered snapshots, QTVR, or walkthrough videos of the 3D models of different buildings, photos of them before the earthquake, and their geo-referencing by using the UTM system on satellite photos. Their names are provided in five languages with the date, physical condition, and material of each building, the history of the buildings from multiple references, people that contributed to the 3D CG process, and several other data. The Website also renders maps of buildings on the satellite photos of sites that enable users to gain access to building information (Andaroodi, Kitamoto, 2010).

5.2. Virtual reality demonstration

We represented QTVR videos of the virtual citadel on the Bam 3D CG Website, which allowed users to look at different directions with variable resolution. However, the interactivity offered by Quicktime VR was limited, because users could not move from the camera location to another point. A more advanced mechanism is to use a virtual reality system for real-time rendering. We presented the Bam 3D CG reconstruction as part of a virtual reality (VR) demonstration. The VR space of the completed 3D CG models is intended to be the basis for future restoration work.

The space was built using the OmegaSpace VR presentation software developed by Solidray Co., Ltd. OmegaSpace is also space construction software that enables real-time rendering in a PC environment and can be used in various fields. It can also be extended to a cyberspace type of system on a network, allowing two or more users to simultaneously use a single VR file. This enables the VR space to be shared and cooperative work to be done in it.

The model was output in VRML form with coordinate information to create a VR file and was read into OmegaSpace. The model was lit arbitrarily and two or more cameras were set up in each building. The walk-through was done by switching cameras with a joystick. We also added a collision-detection mechanism to prevent the operator from walking into walls and other objects in the model.

The VR demonstration enabled users to interact with computer-simulated spaces and walk virtually inside the buildings displayed on the screen. This might be the only chance for them to discover the heritage of Bam. We used a Z-800 3D Visor head-mounted display to test the effectiveness of the VR technology for our model.

The preliminary VR demonstration was presented in a workshop that was held at the citadel of Bam in September 2006. The open house at NII in June 2007 also held a virtual tour inside the digitally restored citadel. A virtual demonstration was broadcast by NHK in its 'SOS from World Heritage' program in May 2006. The VR demonstration revived buildings of the citadel of Bam, which are now impossible to visit in the real world (Ono et al., 2008b).

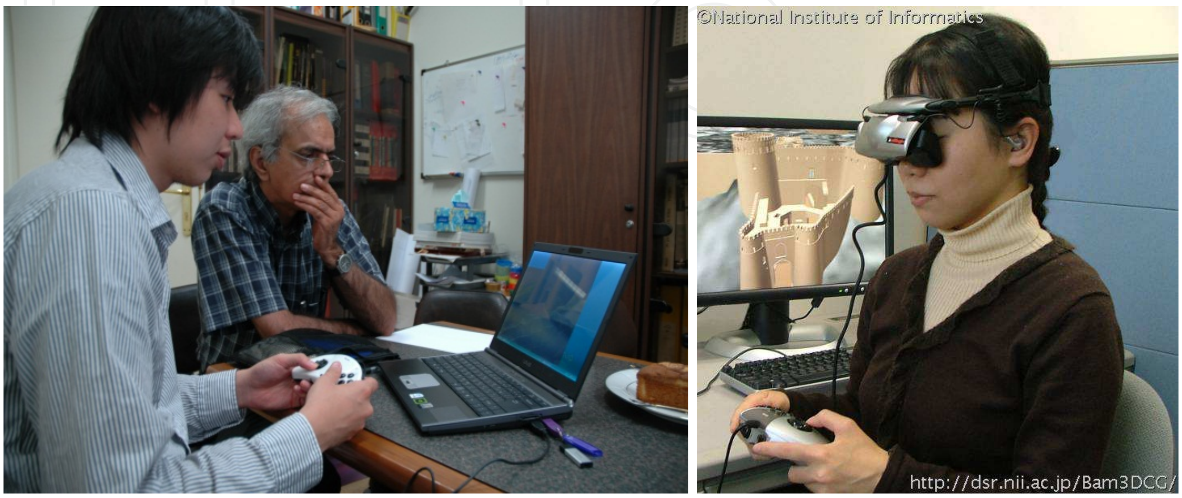

Figure 12. Test of virtual reality demonstration in Bam 3D CG Reconstruction

The main limitation of the VR system is that users need to go to places where special devices are available. It may be useful for specific exhibitions, but this is not a good solution for the general public. The best solution is to build a system on the Internet where users can interactively navigate through the 3D model at any time from any place with a browser.

The simplest solution available is to use a virtual reality modeling language (VRML) version of the 3D models online so anyone with a VRML browser can download the data and interactively render the 3D model. We could not use this method as free distribution of data was not considered. The ideal solution is to protect the original model on the server side, and only transfer the rendered output to the client side in an interactive manner in real-time. We are now seeking a solution to fulfil this idea (Kitamoto et al, 2011).

6. Conclusion

The 3D CG reconstruction of the citadel of Bam was a post-disaster effort to virtually revive large adobe structures after its destruction in the earthquake. We investigated several techniques to create a 3D CG reconstitution of the site. 3D CG manual modeling was our best solution as the site had been destroyed and direct techniques of measurement could not be applied. We used a photogrammetric 3D map that was reconstituted from aerial photographs as a basic resource (IFCA project). We added several other heterogeneous data such as on-site photos, videos, and sketches to complete knowledge of the original shapes of the buildings.

We collaborated with various 3D modeling teams as part of an academic-research effort. There were two phases of 3D modeling to reconstitute all extremely important buildings in the citadel. First, the CG modelers directly used heterogeneous data for 3D modeling. Unfortunately, the initial data were more incomplete than we expected, and several spaces were ambiguous in form. The work of 3D modelers was controlled several times to create a precise 3D model and 10 buildings were completed from 2005 to 2007.

Later, we developed CAD-based 3D drawings as basic resources in the second phase by gradually implementing the heterogeneous data. The modelers used 3D drawings as basic resources and just defined faces between lines to complete the 3D model. This second phase lasted till 2009 and more than 20 buildings were reconstructed in the citadel. We represented our results at a conceptual level on an ontology-based Website. The output was several rendered images, QTVR, and walkthrough videos. Data were linked with knowledge of the buildings and represented their history, material, and locations.

The virtual reality (VR) demonstrations of the reconstructed buildings were presented inside the OmegaSpace tool, and were viewed with an HMD in 3D by several visitors of buildings that had been destroyed and did not exist in the real world.

Our future work is to complete 3D CG reconstruction by automatically or semi-automatically generating less important areas of the citadel such as its surrounding walls or residential districts.

We investigated ways of building a system on the Internet where users could interactively navigate through a 3D model of the citadel with a browser at any time through an online Virtual Reality system.

The Citadel of Bam is under physical reconstruction now but several locations such as the Governor Section have suffered serious damages and it seems to be very difficult to physically restore them. Our Virtual Reconstruction is the only chance for the visitors to view the site. Therefore a VR theatre that is constructed in the site beside the Citadel can provide the chance for the visitors to see the heritage in its original shape before the earthquake. The 3D stereoscopic image that is provided by a 3D projector and viewed on a wide screen in a VR theatre can present a better 3D stereoscopic presentation effect and help the visitors to experience a high quality three dimensional walkthrough inside the heritage.

Another application is to provide an Augmented Reality (AR) presentation of the site with different tools. The visitors can experience the destroyed heritage and the 3D CG reconstructed images provided by AR system at the same time and compare them together.

Different VR or AR presentation systems of the destroyed heritage that is reconstructed by 3D CG techniques are the key applications to revive the site virtually and to preserve it for future generation.

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7. References

Aarmaanshahr, Architecture and Urbanism Consulting Engineers. (1993). *Studies of the master plan of Bam region and Bam city, volume 1*. Ministry of Housing and Urban Planning, General Office of Kerman Province. Kerman

Andaroodi, E. & Kitamoto, A. (2010). Architectural Heritage Online: Ontology-Driven Website Generation for World Heritage Sites in Danger. *Proceeding of the Digital Heritage, Third International Conference, EuroMed 2010. Lecture Notes in Computer Science*, 6436, ISSN: 0302-9743, Cyprus, November 2010

Aasefi Heravi, A.H. M. (1964). *Seljuqs and Ghaz in Kerman*. Tahouri. Tehran

Adle, C. (2004). Oldest Qanat System in Iran Was Discovered. Cultural Heritage News Agency. Date of access 2012/03/10. Available from: http://www.chn.ir/News/?section=2&id=9252

Ahmadi, N. (2008). Pottery dated back 5,000 years were discovered in the Citadel of Bam after removal of debris. Cultural Heritage News Agency. Date of access 2012/03/10. Available from:http://www.chn.ir/news/?Section=2&id=47372

Ataai, M.T. & Ahmadi, N. & Zare, Sh. (2006). the area of Bam and Baravat was inhabited during the Achaemenid and Parthian periods Cultural Heritage News Agency. Date of access 2012/03/10. Available from: http://www.chn.ir/News/?section=2&id=35866

Cyark. (March 2012). Available from:http://archive.cyark.org/

Dublin Core Metadata Element Set. (March 2012) Available from: http://dublincore.org/documents/dces/

Ferdowsi, A. (1974). *Shahnameh, volumn 5*. Pocket Book Co. Tehran.

Grün, A.& Remondino, F. & Zhang, Li (2004). Photogrammetric reconstruction of the Great Buddha of Bamiyan, Afghanistan. *The Photogrammetric Record,* Volume 19, Issue 107, (September 2004), pp. 177-199. Online ISSN: 1477-9730.

Ibn HAWQAL, M.A.K. (1966). *Surat-al-Ardh*. Cultural Foundation of Iran. Tehran.

International Council on Monuments and Sites. (March 2012). Available from: www.international.icomos.org/charters/charters.pdf

International Scientific Committee for Documentation of Cultural Heritage. (March 2012). Available from:http://cipa.icomos.org/

Kacyra,B. (2011). Ancient Wonders Captured in 3D. *TEDGlobal*. (March 2012). Available from: http://www.ted.com/talks/ben_kacyra_ancient_wonders_captured_in_3d.html

Kitamoto, A. & Andaroodi, E. & Matini, M. & Ono, K. (2011). Post-Disaster Reconstruction of Cultural Heritage: Citadel of Bam, Iran. *Proceeding of IPSJ SIG Computers and the Humanities Symposium*, Kyoto, December 2011.

Mehryar, M. (2004). *The History of the Citadel of Bam*. Iranian Cultural Heritage and Tourism Organization, Tehran.

Matini, M. R. & Andaroodi, E. & Kitamoto, A. & Ono, K. (2008). Development of CAD-based 3D Drawing as a Basic Resource for Digital Reconstruction of Bam's Citadel (UNESCO World Heritage), *Proceeding of Conference on Virtual Systems and Multimedia Dedicated to Digital Heritage (VSMM-Full papers)*. ISBN: 978-963-8046-99-4, Cyprus, October 2008

Matini, M. R. & Ono, K. (2010). Accuracy Verification of Manual 3D CG Reconstruction: Case Study of Destroyed Architectural Heritage, Bam Citadel. *Proceeding of the Digital Heritage, Third International Conference, EuroMed 2010, Lecture Notes in Computer Science*, 6436, ISSN: 0302-9743, Cyprus, November 2010

Nourbakhsh, H. (1974). *Arg-e-Bam and a Summary of the History of Urbanism in Iran* , Cultural Heritage Documentation Center, Tehran

Omega Space ®. (March 2012). Available from: http://www.solidray.co.jp/product/omega/index.html

Ono, K. & Kitamoto, A. & Andaroodi, E. & Onishi, M. & Nishimura, Y. & Matini, M.R. (2008). Memory of the Silk Road -The Digital Silk Road Project. *Proceeding of the Conference on Virtual Systems and Multimedia Dedicated to Digital Heritage (VSMM-Project papers)*, Cyprus, October 2008

Ono, K. & Andaroodi, E.& Matini, M.R.& Einifar, A.& Abe, N.& Kawai, T. & Kitamoto, A & Bouet, O & Chopin, F. & Mokhtari, E. & Einifar, S. (2008). 3DCG Reconstitution and Virtual Reality of UNESCO World Heritage in Danger: the Citadel of Bam. *Journal of Progress in Informatics*. 5th issue. (March 2008). pp. 99-135. Print ISSN: 1349-8614 , Online ISSN : 1349-8606

Tayari, H. (2005). *The Citadel of Bam.* Bam Recovery Office, Iranian Cultural Heritage, Handicraft and Tourism Organization, Tehran

Thornes, R. & Bold, J. Documenting the Cultural Heritage (1998). The J. Paul Getty Trust. 1998. (March 2012). Available from: http://archives.icom.museum/object-id/heritage/index.html

United Nations Educational Scientific and Cultural Organization [UNESCO], World Heritage Centre [WHC]. List of World Heritage in Danger. (March 2012). Available from: http://whc.unesco.org/en/danger

Vaziri Kermani, A. (1967), *Geography of Kerman*. Scientific Publisher. Tehran