INTRODUCTION

This paper presents an analysis of damages to the vaulted structures of Bam and Arg-e-Bam, Iran, which were severely hit by the 2003 earthquake. This work was done in the framework of the French contribution to the Islamic Republic of Iran after the earthquake, with a partnership between ICHTO (Iranian Cultural Heritage and Tourism Organization) and CRATerre-EAG.

ARG-E-BAM AND THE EARTHQUAKE

2.1 Brief history of Arg-e-Bam

It seems that the first settlements in the area began when Achaemenians (579-323 BC) built a fort in the area. Later on, during the Parthian rule, the fort was expanded further and it became Arg-e-Bam, the Citadel of Bam. During the following centuries, Arg-e-Bam was subject to several wars. Until 1932 Arg-e-Bam was used a garrison and it seems that at this time nobody was living anymore in the old city at the foot of the citadel. Therefore, since this time, Arg-e-Bam and the city have been totally abandoned.

Arg-e-Bam combined the development of a castle and a human settlement, with the city at the feet of the castle. This brief history shows that beyond the usual evolution and development of every human settlement, Arg-e-Bam faced many wars. They led to constant remodelling of the castle and settlement: Repairing the damaged structures, rebuilding what was ruined and, adding fortifications and new buildings next to each other.

2.2 Brief on the earthquake

On 26th December 2003, the earthquake struck Bam area at 5.28 AM local time lasting 12 seconds for the major tremors. It was evaluated between 6.3 and 6.6 on Richter’s scale. It left about 37,000 dead, 15,000 injured, 75,000 homeless and between 50 to 80 % of the city of Bam destroyed. The earthquake has been very devastating because its hypocentre was just below Bam, on the South-East part, at around 7 Km depth and it had a vertical motion of 1 G and a horizontal one between 0.7 to 0.8 G.

2.3 Arg-e-Bam before restoration

Arg-e-Bam was totally abandoned since 1932 and may be, even before for the city part. Therefore without any care and even with the little annual rainfall the earth buildings were severely deteriorated by weathering. Therefore before restoration works, what were left were ruins and especially enormous damages for the vaulted roofs. The parts which were the best conserved were the Stables, the Barracks, and the citadel itself, as they were used until 1932.
2.4 *Arg-e-Bam before the earthquake*

During the last few decades, the restoration work attempted to respect the existing structures. Attention was mostly paid to get back these buildings as close as possible to their former aspect. The main problem of these restoration works was that they had not the foresight to strengthen the old structures. No bond had been made between the damaged structures and the repairs, as shown in Figs. 1-4.

Thus, the restoration has been more a cosmetic approach: to return the same aspect to these buildings while redoing facades with cladding of new adobes and doing some traditional plasters on some walls.

3 ANALYSIS OF TYPOLOGIES

3.1 *Arches*

Arches in Bam area are always segmental ones and they present most of the times the same proportions, which are given in the following examples: the centre is either at half or at 2/3 of the span below the springer line (Figs. 5 and 6). An interesting type of an arch has been developed: there were several cases where arches were made with several courses of adobes laid tangent to the radius that means flat (Fig. 6).
3.2 **Vaults**

Vaults in Bam are most of the time slightly segmental ones. The centre is just a little below the springer line. There is not really any rule for their proportions (Fig. 7).

![Figure 7: Segmental vault, Bam.](image)

Bucket vaults are also a common shape in Arg-e-bam. These vaults are extremely flat and exert a lot of thrust. The proportions of these vaults vary a little (Fig. 8).

![Figure 8: Bucket vault, Bam, Caravanserai.](image)

3.3 **Domes**

There are mostly two types of domes seen in Arg-e-Bam: domes on squinches (Fig. 9) and domes on pendentives (Figs. 10-12). The domes on squinches are either on a square or rectangular plan. The domes on pendentives have mostly a section based on a bucket pointed arch. These domes are also built on a square or rectangular plan.

![Figure 9: Dome on squinches, Arg-e-Bam office.](image)  
![Figure 10: Dome on pendentives, Mirza Naïm.](image)

![Figure 11: Dome on pendentives, Caravanserai.](image)  
![Figure 12: Dome on pendentives, Stables.](image)
The dome shown in Fig. 13 is a typical dome on squinches and it revealed a failure of the back fillings, which is quite a typical failure mechanism for all domes in Arg-e-Bam. In many cases the filling of the haunches loses its cohesion and become powdery. This kind of filling should be done with a cohesive soil so as to load the haunches in a monolithic way. It seems that the materials used for this purpose were all kinds of waste soils and materials which had not a very high cohesion. The earthquake disintegrated the existing little cohesion and almost liquefied the filling.

Figure 13 : Dome on squinches, near project office.

4 ANALYSIS OF PATHOLOGIES AND THEIR CAUSES

4.1 Effect of the earthquake on structures

Earthquakes severely affect buildings with shear, torsion, bending and uplifting forces. In Arg-e-Bam and Bam, buildings presented the typical collapse and crack pattern. It is interesting to note that the shear cracks developed just below the line of thrust of the segmental arches (Figs. 14 and 15). Note that these cracks developed in the restored wall made with new adobe blocks.

Figure 14 : Shear cracks in cladding, Arg-e-Bam.  
Figure 15 : Shear cracks in bearing wall of a vault.

Filler walls below the vaults and the tympanums cannot be linked with the masonry beside. Therefore they tend to separate and split, as it happened in the Barracks (Figs. 16 and 17).

Figure 16 : Shear cracks and split of tympanum.  
Figure 17 : Split of tympanum/vault.

Vaults are built with vertical courses, which are slightly inclined. This is the typical way to build vaults with the Nubian technique. Blocks are normally laid on a plan which is inclined by a few degrees from the vertical. In several cases vaults in Arg-e-Bam presented warped courses: they were laid on a plan inclined from the vertical but the blocks were not laid flat on this plan.
The results were that the courses at the end of the vault, towards the tympanum, tended to collapse more than normal (Figs. 18 and 19).

The Caravanserai presented enormous damages on the western part. This building was oriented North-South and the entire east façade of the first floor collapsed. Tympanums of the vaults fell as well as the columns of the domes. Another reason for the severe collapse was the buttresses on the West. They tilted but they had also a different inertia and stiffness than the structure. As a result, the combination of both things created such a result (Figs. 20 and 21).

Pendentives of a dome usually behave well during the earthquake. The reason is that they are heavily loaded as they transfer the thrust of the dome. Domes rather get damaged on their sides, above the arches/side vaults which support it. This happens because the thrust in this part is different than in the pendentives and is also less intense (Figs. 22 and 23).

4.2 Stability limit of structures

A general remark can be done for nearly all vaults and domes in Arg-e-Bam and Bam area: The system vaulted structure/wall is most of the times at the limit of stability under static conditions: the line of thrust (LT) should remain in the middle third of the entire masonry. This is rarely the case for the structures which were still standing.
Therefore, already under static condition, the wall is subject to tilt and to shear. Thus, the earthquake emphasizes this stress tremendously and has no mercy on the structure vault/wall which is at its limit of stability (Fig. 24).

The analysis for the vault below in Arg-e-Bam, Fig. 25, follows the same principle as for the first vault in Bam (Fig. 24). The difference is that this structure did not originally have a front wall and therefore the box system was not really acting to reinforce the structure. This vault behaved extraordinarily well under the stress of the earthquake and it challenges the rules of stability, even under normal conditions.

The vault in Fig. 26 is at the limit of stability under normal conditions, as the line of thrust (LT) is tangent to the limits of the middle third. LT moves with the tremors of the earthquake and as a result the vault cracks. The cracks were emphasized by the different rigidity of the vault and its filling.
Domes have a different behaviour than vaults and they can withstand more stresses. They behave like a cohesive shell and even if a support collapses, they will be damaged but will still stand. Domes on pendentives were most subject to collapse: the structure of a dome/column is also most of the time at the limit of stability. The columns/pendentives are in general not loaded enough. LT goes out of the middle third of the columns and under the stress of the earthquake often one column collapses. Fig. 27 of this dome on pendentives shows the shell behaviour of the domes very well. The latter only stands on three columns and has minor shear cracks.

4.3 Construction and material quality

The restoration works show nice finishes, but in many cases the construction quality was rather low. Iranian masons and builders have a long tradition of building with adobe blocks and vaulted structures. Unfortunately this knowledge has disappeared a lot for vaults made of adobe. The analysis of the remaining structures in Bam area showed that often vaults are limit to be stable under normal conditions.

The restoration in Arg-e-Bam also shows a poor workmanship. All restorations look very neat and well done, but the wounds left by the earthquake reveal many mistakes and at times badly executed works. It seems that local masons lost relatively the skill which can insure good quality works. They remembered vaguely how to build, but they did not have anymore the gestures and practical knowledge.

4.3.1 Mortar

The mortar used, most of the time, for restoration was too clayey. Therefore, it developed many shrinkage cracks while drying. These cracks are detrimental for the strength under normal conditions, and the earthquake had no mercy on such works. Straw is observed in the mortar of ancient vaults.
4.3.2 Bonds
Bonds are in general quite bad, both for the walls and the vaulted structures. Very often there was no care for the bond pattern. When this is combined with the clayey mortar, it just creates split joints which increase with the earthquake (Figs. 26 and 27).

Figure 26: squinche, bad mortar & bad bonds.  
Figure 27: vault, bad bonds.

4.4 Restoration works
It has already been mentioned in section 1.4 that the restoration works had no structural bond with the original masonry. Many examples showed the failure of vaulted structures because of the damage of the bearing wall. In many cases the damages and/or collapse were due to partial or total failure of the bearing walls. The restoration conducted for the vaults and domes were of a poor quality. The combination of bad bonds and high clay content in the mortar contributed with the earthquake to further split the various courses and shear the whole structure.

5 CONCLUSIONS
The “cosmetic” restorations undertaken the last decades affected severely the behavior of the structures during the earthquake. New facades were done on ruins without giving back the structural strength of the walls. Nearly all original vaulted roofs were either severely damaged or collapsed, and the ones which had been rebuilt were resting on structurally weak walls.

Other important aspects which are responsible for the damages are the following:
- The system of wall/vault-dome was often at the stability limit under static condition.
- The quality of works undertaken during restoration was not so good, due to poor local skill.
- Heavy weight of adobes used for the vaults and domes.

Despite these reasons, one should not actually forget that the earthquake was extremely severe and that newly built structures also suffered a lot from the tremors. The maximum of the collapsed structures were “modern ones” and it has been estimated by various sources that more than 60% of the deaths were caused by these recent buildings (concrete and steel frame ones).

The questions which had been raised at the time of the report were:
- What has to be conserved?
- Do we want to conserve the original ruins before restoration?
- Do we want to conserve/restore the look given by the restorations?

Since the report on this analysis was given to the concerned authorities, no news has been given to the author regarding the works undertaken in Arg-e-Bam.