REHABILITATION OF HISTORIC MASONRY DOME OF IMAM AL-ABBAS BIN ALI SHRINE USING CFRP SYSTEMS

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ABSTRACT

This paper describes the engineering procedures involved in the rehabilitation of the masonry dome of the Al-Abbas bin Ali shrine, located in Karbala city in Iraq. Severe cracks appeared in the dome as a result of blast action and direct tank hits in 1991, exacerbating the already existing cracks due to foundation settlement and inappropriate strengthening methods used to stabilise the dome in the past. This paper reports on the carbon fibre reinforced polymer (CFRP) strengthening system adopted to repair the dome. Both laminate and fabric systems were used in this project. Following the completion of the repair project, inspection and monitoring are performed periodically to evaluate the effectiveness of the repair system.

INTRODUCTION

Many historic monumental masonry structures are still in service all over the world and a significant number are of cultural and artistic value. These structures are typically masonry arches, barrel vaults, cross or groin vaults, cloister vaults, and domes. Such structural forms are also very common in public and residential buildings.

Masonry structures have shown their vulnerability to major events like earthquakes, bomb blasts and strong winds, in addition to foundation movement. Traditional techniques have been employed in the past to rehabilitate and retrofit existing historic masonry structures.

With its well-recognised advantages, the use of fibre reinforced polymer (FRP) is fast becoming the preferred choice in the strengthening and rehabilitation of existing structures, ranging from the retrofitting and rehabilitation of buildings and bridges to the restoration and strengthening of historic monumental masonry structures. Historic structures such as masonry vaults and domes are mainly strengthened by FRP because of its very high strength-to-weight ratio, which helps avoid the most critical failure mode of such structures. In many seismically-active countries, the use of FRP materials for strengthening and retrofitting existing structures has been widely introduced due to recent earthquakes and natural disasters. Importantly, FRPs are particularly effective for strengthening structures against seismic/dynamic loads since they have very low weight, which makes them ideal for this type of retrofit. Based on the recently published Italian FRP guidelines (CNR-DT 200/2004), along with a number of research studies all over the world on the use of FRP for strengthening masonry structures (ACI 440M (2004), Galati et. al. (2006)) this technique has been put into practice for the last 10-15 years

Several studies have been conducted to evaluate the performance of CFRP-strengthened masonry structures. For example, Stratford et al. (2004) carried out a study using Glass Fibre Reinforced Polymer GFRP in solid bricks to strengthen shear panels. Alcaino Santa-Maria (2008) adopted the use of FRP to strengthen a structure of hollow clay brick subjected to shear loading. A complete study and finite element modelling for strengthening historical structures built with masonry brickwork was presented by Cuzzilla (2009) which showed that the performance of FRP-strengthened walls is highly dependent on the type of masonry and the FRP layout.

Strengthening of masonry structures with FRP systems should be consistent with the Building Code Requirements for Masonry Structures (ACI 530-02, 2002) or equivalent design codes. No additional requirements are necessary for serviceability evaluation except for the reduction for creep rupture in service. It is also recommended in ACI 440M (2004) that the serviceability of a masonry member (deflections, crack...
widths) under service loads should satisfy the applicable provisions of TMS 402-02 (2002). If deflection and crack width requirements are not satisfied prior to strengthening, supplementary methods may need to be implemented to satisfy these requirements.

To ensure the durability of FRP strengthened members, the following factors should be taken into account (CNR-DT200 2004):

- Intended use of the strengthened structure.
- Expected environmental conditions.
- Composition, properties, and performance of existing and new materials.
- Choice of the strengthening system, its configuration, and construction details.
- Quality of workmanship and the level of control.
- Particular protective measures (e.g., fire or impact).
- Intended maintenance program during the life of the strengthened structure.


DESCRIPTION OF DOME STRUCTURE

The shrine of Al-Abbas bin Ali is located in Karbala city in southern Iraq. The historical masonry structure shrine was built around 1150 AD during the Seljuk dynasty. Lime and gypsum were used as mortar materials between the bricks in the structure of the dome. Many strengthening projects have been applied to the shrine since that date, but most of these strengthening projects were not very wise and used only basic tools and were based on poor designs.

The shrine dome is a cross-tie bow dome. The height from the ground to the base of the dome is 20 m., and the height of the dome itself is 12.730 m. The largest radius of the dome is 8 m with a 15.125m bow arch. Figure 1a shows the schematic diagram. In 1955 the dome was covered externally with gold leaf, as shown in Figure 1b.

The dome took direct hits from Iraqi army artillery and tanks in 1991 during a revolt against the regime. These hits caused serious damage and severe cracks to the structure. Figures 2 and 3 show the external and interior damage caused by these hits. Longitudinal and horizontal cracks were generated in the masonry dome structure. A temporary repair was carried out after 1991 to refill these cracks with cement and embed different sizes of steel sections within the bricks of the dome to strengthen it, as shown in Figure 4. However, this system did not
solve the problem completely and the cracks continued to widen. An urgent strengthening project was needed to prevent further deterioration and restore the structural behaviour of the masonry structure.

Figure 2. Damage from artillery and tank hits in 1991

Figure 3. Steel beam embedded in masonry dome

Figure 4. Lateral steel support causing damage to dome

STRENGTHENING PROGRAM

Crack repair

The repair and modification program for the Al-Abbas dome commenced in June 2011. The initial phase of this program consisted primarily of closing the existing cracks with epoxy materials. Superfine epoxy cement (Sikagard-720 EpoCem) was used to seal the cracks in mortar and bricks. The Sikagard material properties are shown in Table 1 below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Compressive Strength (MPa)</th>
<th>Density (kg/litre)</th>
<th>Mix ratio</th>
<th>Curing (Days)</th>
<th>Maximum mixing speed (rpm)</th>
<th>Bond strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sikagard-720 EpoCem</td>
<td>25</td>
<td>2</td>
<td>Component A:1</td>
<td>5</td>
<td>400</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Component B:2.75 Component C:15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The inside surface of the dome was cleaned thoroughly. All surfaces were prepared using an air gun to remove all dust and loose particles. The Sika EpoCem components were mixed for three minutes before application. Injection hole heads were attached to the cracked areas as shown in Figure 5. Epoxy cement was applied through these heads to fill all vertical and horizontal cracks. After all cracks were filled completely the injection heads were removed and all surfaces levelled using a grinder. Sikadur 31 thinxotropix epoxy resin adhesive
mortar was then applied to provide a sub-base surface for the CFRP application. Figure 6 shows the Sikadur 31 application to one of the filled cracks.

**Figure 6. Application of Sikadur 31 thinxotropix epoxy resin adhesive mortar**

### CFRP strengthening

CFRP laminate and fabric systems were used in the retrofitting of the dome’s brickwork. Sika CarboDur S5 12/80 CFRP laminate (Sika CarboDur data sheet) was used. The properties of this CFRP are shown in Table 2. The surfaces inside the dome where the CFRP was to be applied were prepared and levelled first. Thinner was used to clean all surfaces of any grease, oil and dust that may have reduced the adhesion between the CFRP and the masonry sub-structure. Ten minutes were allowed after cleaning to enable the surface to dry completely. A thin layer of Sikadur 30 adhesive (Sikadur 30 data sheet) was then applied to the CFRP Sika CarboDur S5 laminate surface, and a 3 mm layer of Sikadur 30 adhesive was applied to the cleaned masonry surface in strips 90 mm wide. A rubber roller was used to press the laminate plate on the prepared surfaces until the excess adhesive was forced out from both sides to ensure there was no air gap in the bond zone. The final step in the CFRP laminate application was to clean the surface of the laminate. Figure 7 shows the laminate installed inside the dome.

**Table 2. CFRP laminate properties (Sika CarboDur data sheet)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength (MPa)</th>
<th>Density (g/cm³)</th>
<th>E modulus (MPa)</th>
<th>Thickness (mm)</th>
<th>Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sika CarboDur S5</td>
<td>3100</td>
<td>1.6</td>
<td>165000</td>
<td>2</td>
<td>70</td>
</tr>
</tbody>
</table>

**Figure 7. Application of CFRP laminate**

After the completion of curing of the CFRP Sika CarboDur S5 laminate system, the surface of the entire dome was prepared for the third stage of the CFRP strengthening program. SikaWrap 600 C CFRP fabric (SikaWrap
data sheet) was used in this phase. Table 3 illustrates the properties of the CFRP fabric. A wet lay-up system was used, consisting of three main components: adhesive primer, two-part Sikadur 330, and SikaWrap 600 C fabric CFRP.

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength (MPa)</th>
<th>Density (g/cm³)</th>
<th>Thickness (mm)</th>
<th>Elongation at break</th>
</tr>
</thead>
<tbody>
<tr>
<td>SikaWrap 600 C</td>
<td>3800</td>
<td>1.81</td>
<td>0.331</td>
<td>1.55%</td>
</tr>
</tbody>
</table>

Adhesive primer was used to improve the bonding of the composite to the substrate. It is a two-part epoxy product with low viscosity and 100% solid content. It has the ability to penetrate the substrate and to bond to a dry masonry surface. SikaWrap 600 C fabric is made of high tensile strength carbon fibre and supplied in unidirectional tow sheets 300 mm wide. The fibres are held together with a backing grid and rolled together with a plastic sheet. The nominal thickness, based on the total thickness of the fibres in a unit width, is 0.33 mm. The fibre weight is 625 g/m². Sikadur 330 saturant, a two-part epoxy with 100% solid content, was used to impregnate the fibres to form a composite and to provide bonding to the primed surface. Its compressive strength is reported to be greater than 45 MPa. The pot life of the saturant is 120 minutes at 23°C and it reaches design strength after 7 days.

The Sikadur 330 saturant mix was prepared with a ratio of Part A = 100/Part B = 34.5 by weight and mixed for 3 minutes. A brush was used to apply the saturant to the entire surface of the dome. SikaWrap 600 C CFRP fabric sheets were applied to the prepared masonry surface. Figure 8 shows the inside dome face during the application of the CFRP fabric.

Inspection areas of 200mm x 100mm over some of the major cracks were exposed to monitor crack growth over time, as shown in Figure 9. At the date of writing, the cracks appear to be stable.

CONCLUSIONS

The renovation work on the masonry dome of the Al-Abbas bin Ali shrine is described in this paper. CFRP laminate and fabric systems were used to repair the severely damaged dome of this monumental structure. The strengthened structure is monitored and evaluated periodically to ensure the integrity of the repaired structure.

REFERENCES

American Concrete Institute ACI 530-02 (2002): ACI 530-02, “Building Code Requirements for Masonry Structures”, *ACI Committee 530*,


