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Evaluation of brick domes repaired with expandable grout (Case study: dome of Qazvin Jame mosque)

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Abstract: *There are several restoration methods for brick building such as embedding FRP hank and etc. but using of those have been limited for restoration of historical building because restoration must cause minimum change inappearance. We could retrofit brick building using expandable grout with pre-stressed technique but behaviors of these mortars usually have been unknown for experts. Most of these constructions were used in domes in Iran and numerous domes in historical building indicate essentiality of this research. In this research mechanical properties of expandable grout have been determinate by experiments and then dome of Qazvin mosque was modeled using ABAQUS software as major and minor modeling combination. Results show that depending on little effect of these mortar on dome form, obtained uniform pre-stressing lead to tensile and deformation reduction and finally crack decreasing that this could be effective through the earthquake.*

Keywords: *Dome, Brick, Expandable Grout, Restoration, Qazvin Jamemosque*

Introduction

In past centuries, architects were used brick domes as large spans shield in case of brick structure. These building with large spans and height usually used in religious buildings and sacred places and indicated those greatness (moeeni and Sahab, 2013). Dome is an architectural element that is same as hallow half of sphere. Dome structure made from several materials and its usage history is in prehistoric times. We could say that dome is an arc that was rotated around center axis, so dome has adequate structural strength same as arc and if built properly it could cover large spans(Dangar and Parikh, 2013).

Special properties of historic building among their limits of restoring method, tensile force bearing disability of masonry and this material crispy, make accurate analysis of internal forces and retrofitting methods complex and difficult for such buildings. Although extensive experimental and theoretical study were conducted in field of masonry structure behaviors specially walls and brick infill under gravity and seismic loading since last three decades (Moradi and et.al, 2008), but few experimental and theoretical study were conducted in field of retrofitting of Iranian historic building and brick domes. Professor Hee man was the first one that offered modern analysis base on ancient theories of 17^{th}century in 20^{th} century in field of arch structures. He present a minimum amount for thickness to arch span rate as confident solution by assuming unlimitedcompression strength, zero tensile strength and friction stiffness for masonry (Celik et.al, 2008). Although several methods were suggested in order to retrofitting the brick building such as using FRP, walls strengthening by shoot Crete, adding shear wall and stiffener, epoxy and grout injection in bricks joints and embedding hank to provide structural cohesion, but because of historical building restoration laws limitation, usage of these method limited. Accordance with the restoration laws, retrofitting methods of a historical building must be such that cause minimum appearance change. In addition lack of known of used materials mechanical properties make analysis and retrofitting plan presenting more difficult in these building. Pre stressing is one of the ancient methods that was used for masonry structures retrofitting. Pre stressing method use steel elements for retrofitting cultural heritages that lead to buildings repairing or conservation of them. These elements have been putted on brick elements or within them (Juger et.al, 2003). In this method, generated tensile forces in structure due external loads would neutralize by compression due embedded pre-stressed cables. In this research we will trying that applies pre stressing to brick dome by injecting expandable grout in bricks joints.

Theoretic basis

Looking at architecture history, we see that any structures haven't evolution as such as dome, this evolution accrued via construction of numerous domes by their architects and builders. We could find some structural issues in domes study history that still studying by researchers. Continues studies about domes were proved that builders in addition of knowledge about shape beauty also have been informed of laws related to construction and their stability (Meemarian, 1988).

Analysis of domes crash and collapse is more complex in comparison with other arch structures. First studies were conducted about dome thickness by Kobel (1855), and about domes collapse mechanism by Beket (1877) which were not completely true. First accurate and correct studies about masonry dome behaviors again were conducted by professor Hee man (1967, 1977) (Celik et.al, 2008).

In order to indicating efficiency of suggested retrofitting method, basis principles of domes behaviors have been shown in figure 1. Seem cracks pattern mostly are meridian cracks that create because of walls or supports sliding of domes (ibid). Present forces in dome apply in two orbital and meridian directions at dome that meridian cracks create because of orbital tensile forces at dome. We could conquer tensile forces using expandable grout on areas of dome that there are orbital tensile forces and creating compress due pre stressing and therefore resist creating meridian tensile cracks. Dome internal forces and created cracks pattern have been shown in figure 1.

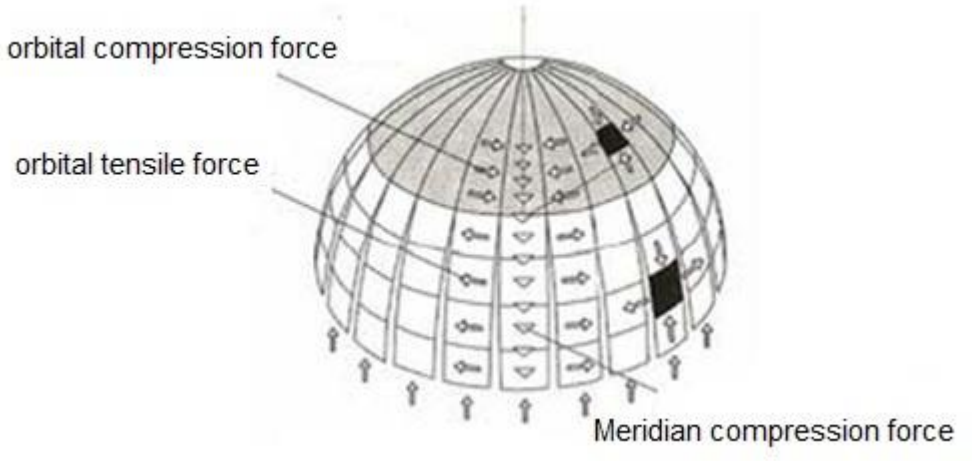

Figure 1- created cracks pattern in dome (writer)

Research range

Gazvinjame mosque is one of the oldest historical buildings of Gazvin city. FakhrolddoleDeylami began building wall of mosqueat 4th century AH at that was uncompleted. At year 393 AH mosque was reconstruct and restored; and at year 413, collapsed part of big arena have been renovated (Research and Documentation Center of the Faculty of architecture and Urban Planning, ShahidBeheshti University, 2004). Present brick dome of mosque start at year 500 AH with effort of Amir KhomarTashEbnAbdollah and completed coincident with some other part of building at year 509 (Ibid). Restoration operation of Gazvinjame mosque was started at 1973 and has been continued until now. Currently restoration workshop is active on repairing the cracks of dome. This dome with 18 meters span and about 9 meters heights has been studied in this research. Dome thickness variable from 1.3 meters at bottom to 1 meter at top of dome (Mojabi, 2005).an

evaluation of this mosque has been shown at figure 2 for better familiarity.

For modeling brick and mortar in ABAQUS software two micro and macro modeling are in use that in the first each brick was modeled and many assembled element were used for modeling brickwork, but in second regardless of brick and mortar separation a general model with mean properties of brick and mortar properties has been used (SaediDaryan et. al, 2009). In the case evaluation of dome of Gazvinjame mosque a mean viewpoint was used to in addition of reducing micro modeling time consuming because of dome large body, and this viewpoint in area of dome that need to injection of expandable grout and mortar joint become model.

As expressed previously, dome inferior part was bearing tensile and meridian cracks seem in this area that dome pre-stressing idea using expandable grout apply to this area by software.

Simple and mean approach that has been used for dome modeling is meridian slices model.Thus a dome was modeled with 20 meridian slices made of brick and mortar between them using contact element that provide sliding possibility in mortar joints. Drucker-Pruger materials have been used for brick modeling.

Figure 2 – Gazvinjame mosque (web site of Parsian higher education institute)

Analysis

In order to determinate expanding rate of mentioned expandable grout and ensure from its proper action on masonry arch pre-stressing firstly it needed that measuring expanding rate of mortar. So a device was designed and made for measuring expanding rate of mortar as figure 3. This device operation based on magnifying length changes (length extending) of applied mortar in a cylinder and transferring this length change with 20x in a slender pipe contain liquid (oil). Length of mortar founded in device that expanding of it has been measured is equal to 50 centimeters. In addition mortar volume expansion meter that was equipped to measured gauge. Length of founded mortar in this device because of device size limited to 10 centimeters but length change accuracy measurement by device gauge is 0.01 millimeter. Depending on mortar length ratio founded in suggested device to founded mortar in standard mortar expansion meter we could say that both devices able to magnifying mortar expansion 100 time.

Masonry arches with 1.2 span and 5 centimeters height on top of arch, 5 centimeter thickness and 20 centimeter width made with brick in laboratory and two tests were arranged with normal mortar and expandable mortar to determining pre-stressing compress force amount product from expandable grout injection to brick joints instead of normal mortar, and compression force amount product from expansion of mentioned expandable groutwas obtained by comparison ability of bearing of extended load by arches made from normal mortar and expandable mortar, that will expressing future sections.

Figure 3 – texted sample in suggested device (writer)

Built Brick arch because of its more little arch is similar to a direct beam. So we can extend relation of a direct to hinge end beam to this arch close to the line. If sustainable tensile stress of beam before retrofitting is σ, for beam after retrofitting this stress reach x+σ amount that added stress is because of added compress due pre-stressing. So extended load that could be applied to beam also have been increased:

$$\sigma + x = ql^2/8W$$

$$q = \sigma \times 8W/l^2$$

$$q' = (\sigma + x) \times 8W/l^2$$

That l is span length or length of equivalent beam, x is amount of extra stress that beam could bear it after retrofitting and q and q' respectively are sustainable load by beam before and after retrofitting.

Sustained load by arch made with normal mortar has been about 340 kg lesser than sustainable load by arch made with expandable mortar. So:

$$X=61\ Kg/Cm^2$$

According to figure 4, x is amount of pre-stressing compress stress that after plus with present tensile stress of beam increase tensile sustainability of beam. As regards this stress was created by expanding in 5 vertical joints of mortar we could considering pre-stressing amount of each joint as 12 kg/cm^2 which this number will use to modeling the pre-stressing in ABAQUS software.

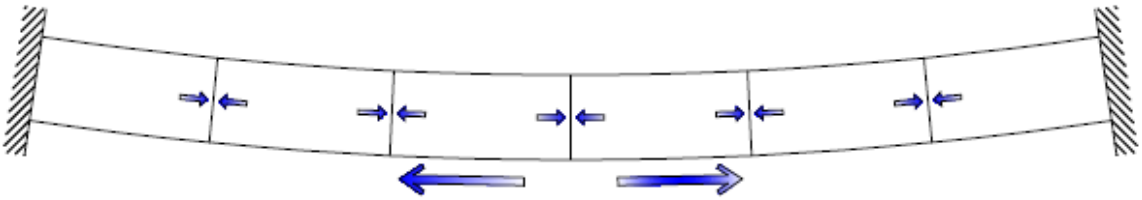

Figure 4 – created cracks pattern in dome (writer)

Used material for research listed in table 1

Material	Ultimate stress (N/mm^2)	Elasticity module (N/mm^2)	Friction angle (Rad)
Brick	57	15500	-
Mortar	-	-	31.79^0

Table 1 – material physical properties (Saedi et. Al, 2009)

In order to simulating free movement of dome on inferior walls, radial shears freedom restricted and 3 cm radial displacement was applied to them. This radial displacement was applied to dome alternatively and with considering explicit analysis than vibration due seismic on dome become model. To simulating pre-stressing due expanding expandable grout, equivalent compression of pre-stressing that obtained about 20 kg/m^2 in experiments was imposed on shared areas between slices as uniform compression load. Analysis results before and after retrofitting was shown at figure 5 and 6.

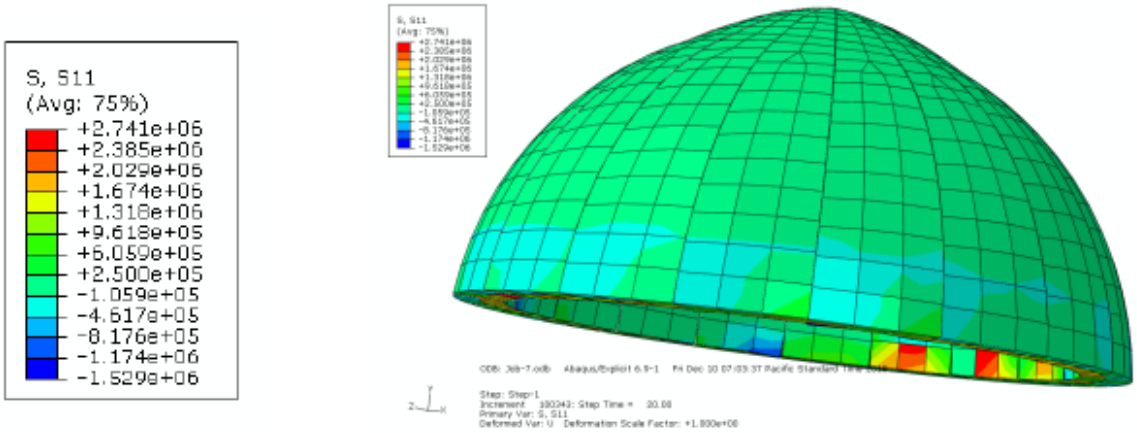

Figure 5 – created radial stress in dome before retrofitting (writer)

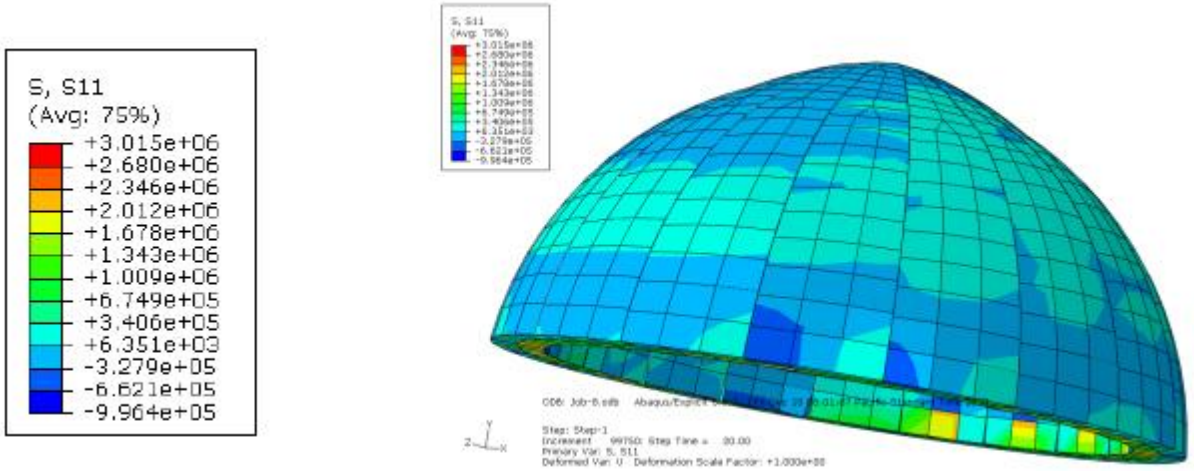

Figure 6 – created radial stress in dome after retrofitting (writer)

Its determinate by observing stress counters that after retrofitting created radial stresses against wall movement have been increased and this has been indicated that compression due pre-stressing applied to dome in tangential or orbital direction in addition of reducing tangential tensile amount restrict slices exterior movement due walls slide. Tangential stress counter before and after retrofitting in figure 7 and 8 have been indicated that tensile in tangential or orbital direction was reduced after retrofitting.

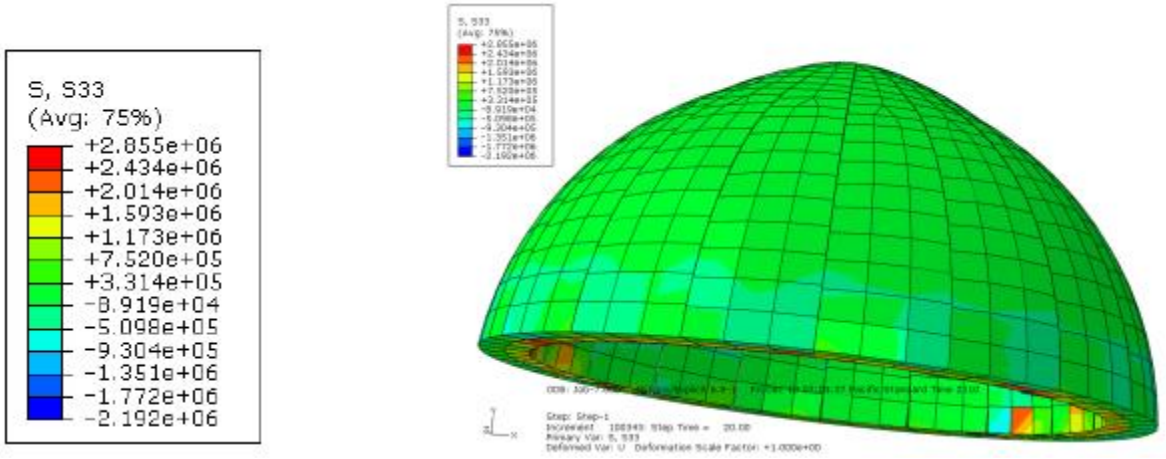

Figure 7 – created tangential stress in dome before retrofitting (writer)

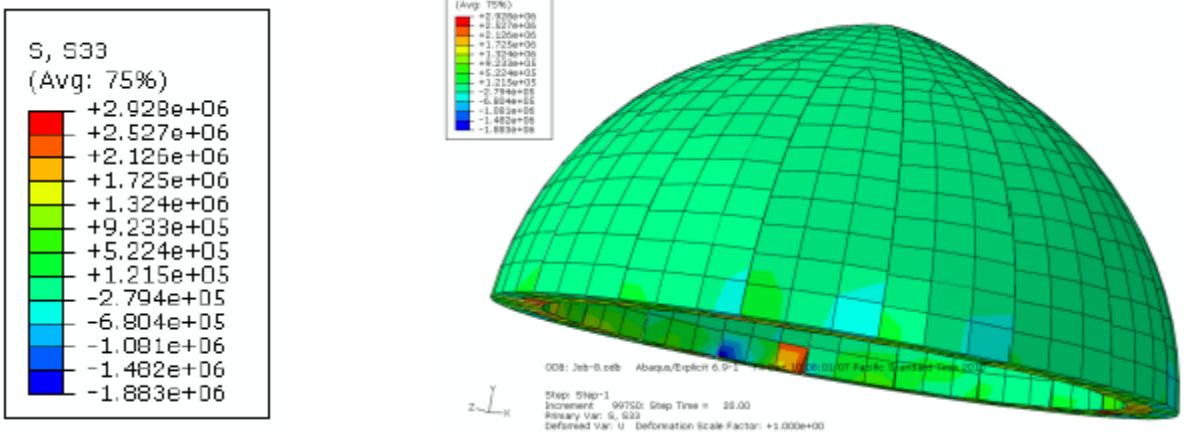

Figure 8 – created tangential stress in dome after retrofitting (writer)

Conclusion

In this paper it has been indicated that using the materials with expanding property become very good choice for retrofitting historical building by pre-stressing method. Because not just reduce cracks by reducing tensile and deformation by creating uniform pre-stress in masonry structure, even were fits well with historical building restoration laws based on minimum falsify in building. By injecting this material in mortar joint at areas of dome that there are tensile stresses, we could reduce cracks and creation of new cracks existence and thus resisting it against vibration due seismic and any other load that lead to exist tensile stresses in dome. This means that there isdesperate need to cooperation between restorations experts and structural engineers.

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