Behaviour Of Strengthened Masonry Arches With Steel Reinforced Grout

P.Saravanakumar, S.Praveenkumar

Abstract: Masonry arch was one of the oldest man-made construction techniques that were in existence. This study deals with the behaviour of masonry arch strengthened with steel reinforced grout (SRG) constituted of steel mesh embedded in a cement matrix that was bonded at either extrados or at the intrados portion of the arch. In this study efficiency of strengthening system in enhancing the performance of masonry arches was investigated. Results in terms of load bearing capacity, structural behaviour and failure mechanism were observed from the experimental investigation. The first stage of investigation involved in characterization of materials that constitute the masonry and the strengthening system by mechanical testing. In the second stage, nine arches were tested by means of load control up to the point of collapse. Experimental results of masonry arches strengthened using steel mesh with spandrel fill form the basis for numerical investigation. The results showed that an arch reinforced with steel mesh placed at extrados was more effective in strength enhancement.

Index Terms: Minimum 7 keywords are mandatory, Keywords should closely reflect the topic and should optimally characterize the paper. Use about four key words or phrases in alphabetical order, separated by commas. Masonry arch, Intrados, Extrados, Steel fiber mesh, Steel reinforced grout, Strengthened arch, Cracks.

1. INTRODUCTION

The increased service loads, aging of the structure, poor maintenance, and movements in the abutments in masonry arch structures necessitate repair or strengthening of structures. It is very difficult to understand and asses the structural behavior of the unreinforced masonry arch existing structure [1]. Modern Non destructive techniques were used to estimate the present condition of the structure. After the detailed structural assessment suitable retrofitting techniques were adopted to repair or strengthening the structure. Conventional retrofitting techniques improved the stability of the structure but it affects the aesthetic appearance of the structure which was very important factor in historic value structures [2].

One of the impressive characteristic of arches was adoptability to the movement in their supporting structure and doesn't cause any harm to the structure until the arch was converted into mechanism by the formation of hinges. By providing suitable reinforcements externally or internally retrieves the structural stability and increase the load carrying capacity of the masonry arch structure [3]. Nowadays many new reinforcing FRP materials were used in repair or strengthening of arch masonry works [4],[5]. The usage of composite materials facilitates the masonry structure to exclude the mechanical shortcomings and to carry considerable tensile stresses [6]. Before starting to use of new materials the compatibility of the materials with existing one must be checked. The unreinforced masonry arches were failed by formation of hinges at the springing, crown and at the weak point in between the springing and the crown either left or right side of the crown. The brittle failure was taken place in the unreinforced masonry arch due to formation of arch displacement mechanism. The main purpose of introducing the reinforcement was to avoid the formation of hinges and this was applicable for both intrados and extrados of the arch. It was worth noticing that the reinforcement can be continuous (applied to the whole structure) or partial (applied to those areas which were considered to be most critical). Composites of ultra-high strength steel chords which were embedded in mortar matrices were also used effectively to strengthen the masonry arch structure [7], [8], [9]. The compatibility and sustainability of steel reinforced grout (SRG) was compared with FRP counterparts for external strengthening of masonry structures. SRG showed superior behavior than FRP in terms of bonding [10], [11]. The masonry arches reinforced with glass fiber and carbon plates at intrados did not reach the state of collapse and it carried more load than the unreinforced arches which was failed due to the collapse. The failure of reinforced arches depends on the bonding behavior of the reinforcements. The strengthening of arch at the extrados result a notable displacement at the springing level and shear sliding was occurred at the time of collapse. [5], [12]. The main aim of the present study was to check the effectiveness of the SRG strengthening technique using high strength steel wire mesh at intrados and extrados of the masonry arch. The formation of hinges, mode of failure, resistive capacity of the arch structure and its deformation were observed for un-strengthened and strengthened arch structure and the results were compared to finding out the efficient approach of SRG technique.

2 EXPERIMENTAL PROGRAM

The experimental investigation was carried out on un-strengthened and strengthened (both extrados and intrados) masonry arch. Initially the experimental campaign was done to characterization of constituent materials. Tension test was carried out on steel fibre mesh and compression test were performed on bricks and cement based matrix.

2.1 Characterization of Masonry Mortar

For masonry arch construction, cement mortar (cement : sand = 1:3 in weight) was used throughout the study. Compressive strength test was performed to obtain the mechanical properties of the mortar in accordance with the specification ASTM C349 [13]. Six cubes were cast (50 mm × 50 mm × 50 mm) and the test was performed after 28 days curing period.

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Testing was carried out in compression testing machine and the average compressive stress was obtained to be 8.67 MPa.

2.2 Characterization of Bricks
Masonry arch was constructed using solid clay bricks (230 mm ×100 mm ×100 mm). The compression and bending tests were carried out on each three brick sample to obtain the mechanical characteristics of the bricks. These tests were carried out in compression testing machine (CTM). The mean compressive strength value was obtained as 11.65MPa and the mean bending tensile strength was observed as 0.88MPa.

2.3 Characterization of Reinforcement
The composite system incorporated in this study to strengthen the masonry structure includes steel fibre mesh. The geometrical and mechanical properties of steel mesh were summarized in Table 1. To determine the mechanical properties, tension test was done on the coupon specimen. Tests were carried out in universal testing machine (UTM) according to the code ASTM D 3039 [14] and the tensile strength and ultimate strain were found. The stress-strain curve results indicates that the material have a slight yielding and behaves linearly to failure. Cementitious grout was used to bond the steel mesh with the masonry structure.

Table 1: *Mechanical properties of the reinforcement*

Property	Steel mesh (Reinforcement)
Thickness (mm)	2.5
Tensile strength, (N/mm^2)	630
Ultimate load (N)	7150
Ultimate strain (%)	12.46

3 ARCH BEHAVIOR AND TEST SETUP

3.1. Arch behavior
To study the behavior of masonry arches the following assumptions were made from past literatures [15] for the masonry arch analysis and design,

1. Masonry structure has infinite compressive strength and negligible or minor tensile strength.
2. Sliding failure of the arch does not occur with the rigid abutment, i.e. the sliding was unrealistic.

As the consequences of these assumptions, masonry arch failed by formation of hinges which converts the arch into mechanism and the stability of the structure was governed by the geometry of the arch. The SRG prevented the cracks from opening and transfers the tension force across the crack and ceases the plastic hinges formation. In some cases instead of prevented the hinge formation, position of the hinges was altered. Therefore the behaviour of the arch was modified and controlled by other failure mechanism. The formation of hinges also depends on the amount and position of the reinforcement and loading pattern. Bonding between the reinforcement and the masonry substrate plays a key role specifically when the steel mesh was placed at the intrados.

3.2. Test Setup
A total of nine semicircular arches of span 850 mm, 430 mm rise above the springing level and 230 mm wall thickness with spandrel fill were constructed for this study. The main purpose of the spandrel fill was to stiffen the arch ring at its edges. The effect of spandrel stiffening plays key role in the load carrying capacity and stability of the structure. It provides some degree of support due to friction between the fill and wall even when the wall was fully separated from the arch ring. Ordinary Portland cement and locally available river sand were used throughout this study. Each three numbers of non-strengthened, extrados strengthened (EXT) and Intrados strengthened (INT) arches were built for behaviour analysis. To study the unstrengthened and strengthened arch behaviour, the loading pattern was arranged in such a way that uniformly distributed load was applied throughout the span using I section ISMB 150 x 80 mm of unit weight 14.90 kg/m^3 placed between the load cell and the specimens. The geometry of the masonry arch was represented in Fig. 1. The constructed arches were placed vertically with the fixed support at the bottom. The vertical displacements at crown were found through LVDT. The load cell and LVDT were connected to the computer and the deflection and load values were recorded through the Aimil DAQ software. The load was applied through hydraulic jack of 1000 kN capacity till the failure of the specimen. From the obtained values, graph was plotted to evaluate the failure mechanism. The loading arrangement and the LVDT setup were represented in Fig. 2. The strengthening technique involves galvanized steel mesh bonded to the structure with the help of cement mortar, and this was termed as steel reinforced grout (SRG). While considering the extrados strengthening, mortar layer of thickness 5 mm was applied above arch ring followed by the galvanized steel mesh of thickness 4.5 mm was placed over the mortar layer. Above the reinforcement a mortar layer of thickness 5 mm was applied. Hence the total thickness of the strengthening system was approximately 15 mm. For intrados strengthening, the same procedure was followed below the arch ring.

4 RESULTS AND DISCUSSIONS
From the experimental study the structural behaviors like failure mechanism, first crack load, ultimate load and deflection were identified for unstrengthened and strengthened arches. Table 2 summarizes the experimental values and the structural behaviors of all arches and the load – displacement curve for arches were discussed in this section.

Fig. 2. Test setup of masonry arch in loading frame.

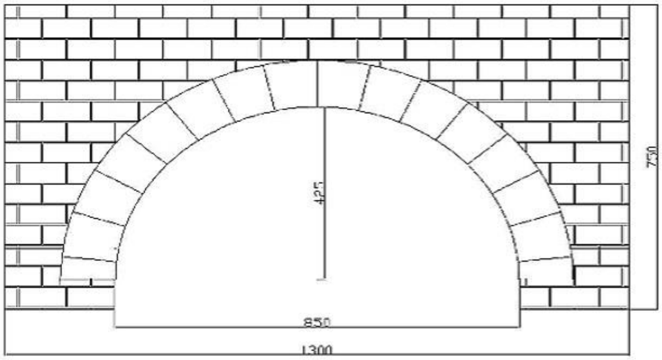

Figure 1 Geometry of the masonry arch.

4.1 Unstrengthened Arch

The lower bound theorem states that the arch was safe when the thrust line was in equilibrium with the external load and lies within the arch ring. The opening of cracks and the formation of hinges takes place when the thrust line does not satisfies the lower bound theorem. The failure or collapse of the structure was triggered by the occurrence of the successive hinges which leads to the mechanism. The failure of the arch was happened when four hinges were formed. Brittle failure was observed in the unreinforced arch due to the formation of hinges (displacement mechanism). Suddenly the failure occurs, without any warning at the maximum load of 21.7 KN and the corresponding deflection of 4.8 mm. The first visible crack formation was considered as first hinge and it was occurred at 18 kN load. The first hinge was formed in the mid portion of the arch at the intrados portion and the second hinge was at the extrados portion, in 1/3 distance right with respect to the first hinge. The third and the fourth hinges formed at the right and left abutment respectively. The position and the order of the hinge formation were represented in Fig. 3.

Table 2: Summary of experimental test results

Specimen & Strengthening Position	Load (kN)		Deflection (mm)		Mode of Failure
	First Crack	Ultimate	First Crack	Ultimate	
Unstrengthened (UN)	18	21.7	4.01	4.8	Hinge Mechanism
Strengthened Intrados (INT)	25	36.5	4.45	7.11	Reinforcement Delamination
Strengthened Extrados (EXT)	28	46.6	4.39	6.12	Masonry crushing, shear sliding.

4.2 Strengthening at Intrados

As for the arches strengthened at intrados with the SRG, the steel mesh delamination and also the crisis of shear sliding at mortar joint were found at failure. Crack formation was discerning above the strengthening system and propagates up to the top of the structure. Masonry crushing was not spotted in this intrados strengthened arch. The first crack was formed at 25 kN load above the strengthening system. The load carrying of the structure and delamination of steel mesh was progressed as long as its contribution in holding the bricks together, after that the load carrying capacity of the arch decreased suddenly. The ultimate load was spotted as 36.5 kN with the maximum deflection of 7.11 mm and the failure ensures due to the delamination of strengthening system from the arch ring. Then the structure undergoes a state of failure. After the first crack due to debonding of SRG the deflection increased rapidly. The failure behaviour of the arch strengthened at the intrados was represented in Fig. 4.

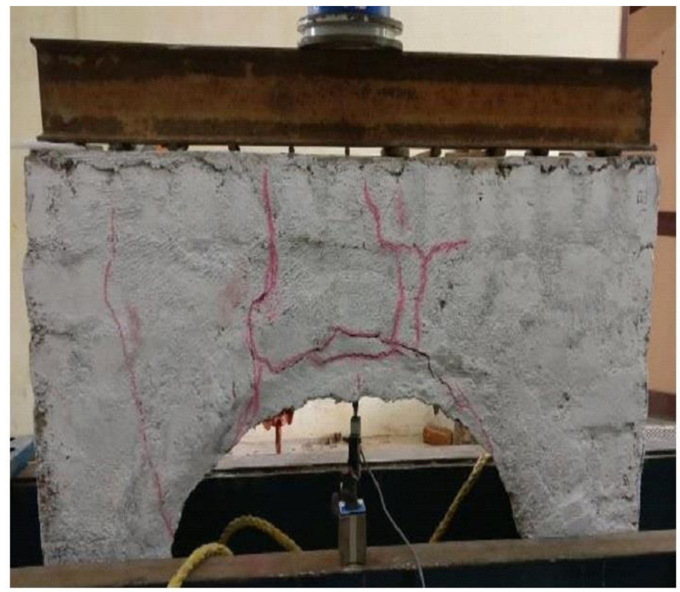

Fig. 4. Failure behaviour of intrados strengthened arch.

4.3 Strengthening at Extrados

The arch strengthened at the extrados with SRG showed two different patterns of collapse like masonry crushing and sliding along the mortar joint. The first visible crack was formed at 28

Fig. 5. Failure behaviour of extrados strengthened arch

kN load and the failure occurred at a maximum load of 46.6 kN due to crushing of the masonry block (keystone) and shear at the mortar joints. While the steel mesh does not get debonded from the masonry substrate, which shows a good bonding behaviour between the reinforcement and the substrate at the extrados of the arch. It was observed that the first crack was formed at the masonry block from the top and it was propagated up to the position of the reinforcement. Beyond the reinforcement, the crack propagation was prevented and the crack was diverted to some other direction. Similarly the shear crack at the mortar joint was noticed at the bottom of the reinforcement which does not propagate above the reinforcement. In this case the propagation of the crack was completely ceased. From the observation, it was clear that the strengthening system not only increases the load carrying capacity but also plays a major role in the prevention of the crack or the propagation of the crack. It was worth noting that the structure did not reach the state of collapse. This was due to the contribution of reinforcement in holding the bricks together. Fig. 5 represented the failure behaviour of arch strengthened at the extrados.

5 ANALYTICAL INVESTIGATION

The load deflection behavior of the strengthened and unstrengthened arch were shown in Fig. 6. For analytical study, a three dimensional finite element model for masonry arch structure comprises of subunits that have different materials and properties was developed by using computer software ANSYS Mechanical APDL to understand the response of individual structural components and their contribution to a structure as a whole (Fig. 7).

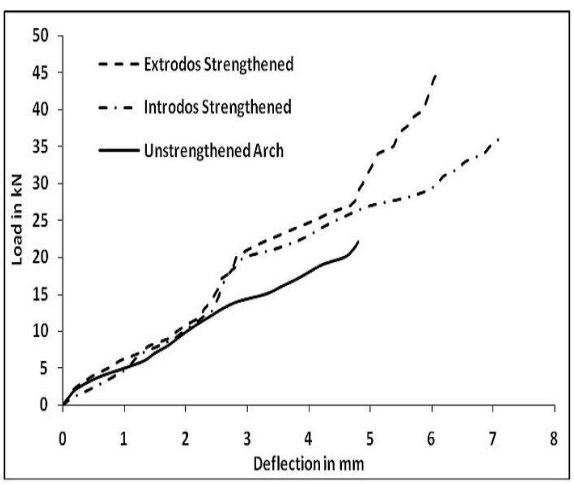

Fig. 6. Load - displacement of Unstrengthened and SRG strengthened arches

Experimental studies of masonry arch with spandrel fill and masonry arch strengthened with the SRG has formed the experimental data base for the finite element modelling. Solid186 was selected as an element type to model the arches. Shell41 was adopted as an element type for the strengthening material. All the material properties were included to develop a ANSYS model. Masonry unit (Brick and Mortar) was considered as a homogeneous material and model the masonry unit as a single material. The masonry unit (composite materials) was assumed as a linearly elastic material. The elastic modulus for the composite material (Brick and mortar) was obtained based on the homogenization

Table 3: Comparison of Numerical and Experimental Study

Method	Unstrengthened		Strengthened (Intrados)		Strengthened (Extrados)	
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
Numerical	18	2.24	25	2.11	28	1.85
Experimental		4.01		4.45		4.39
Numerical	21.7	2.60	36.5	2.46	47	2.34
Experimental		4.80		7.11		6.12

process [16].

$$E = \frac{(Tm + Tu)}{(Tm/Em + Tu/Eu)}\rho$$

Where,

E - Elastic modulus of composite materials
T_m - Thicknessof the mortar
T_u - Thicknessof the brick
E_m - Elastic modulus of mortar
E_u - Elastic modulus of brick
ρ - Efficiency factor

The poison's ratio and unit weight of the composite material (brick and mortar) was taken as 0.2 and 2800 Kg /m^3 [17]. For the strengthening (steel mesh) the poison's ratio and elastic modulus was taken as 0.3 and 147GPa. The stress pattern and the deformed shape for the ultimate load were determined from FEM.

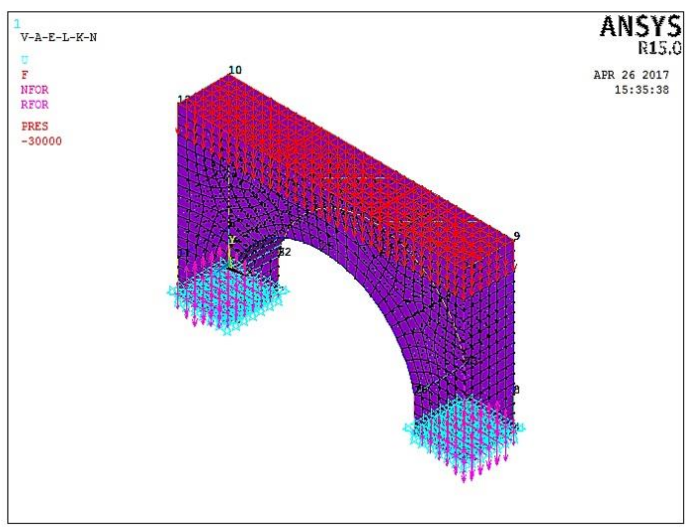

Fig. 7. Modelling of masonry arch using ANSYS

The stress distribution of unstrengthened arch, intrados and extrados strengthened arch were shown in Fig. 8, Fig. 9 and Fig. 10 respectively. For unstrengthened arch, the maximum stress. was 266 kPa and for intrados and extrados strengthened arches were 235kPa and 205kPa respectively. The peak stress was accumulated at the edges starting from the support and continues to top of the structure for the unstrengthened and Intrados strengthened arch. But for extrados strengthened arch the peak stress was accumulated at the supports and only minimum stress is present in the crown portion of the arch.The deformed shape of unstrengthened arch, intrados and extrados strengthened arch were shown in Fig. 11, Fig. 12 and Fig. 13 respectively. The analytical results were compared with the experimental results at first crack load and at the failure load. Table 3 showed the loads and the corresponding deflections values for both analytical and experimental for all arches.

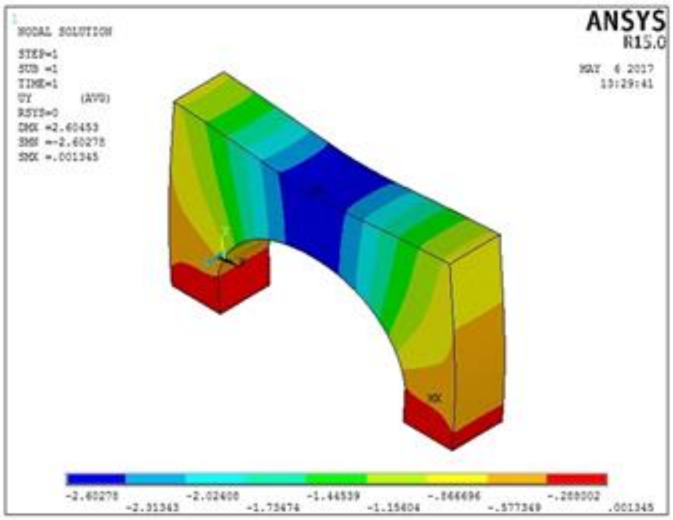

Fig. 8. Stress pattern of unstrengthened arch

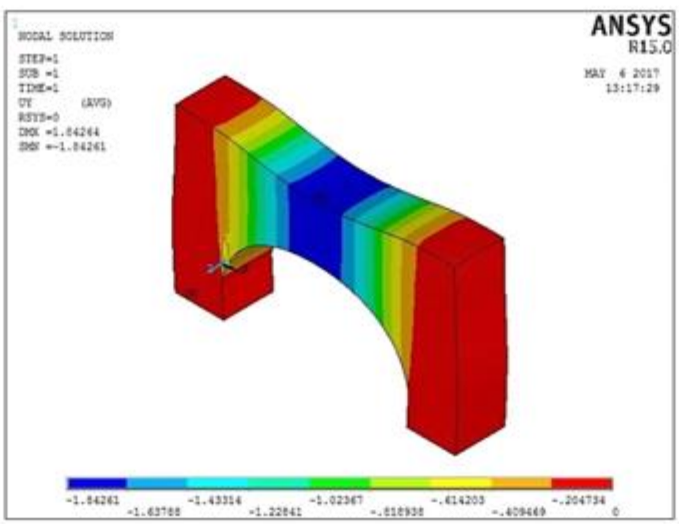

Fig. 9. Stress pattern of extrados strengthened arch.

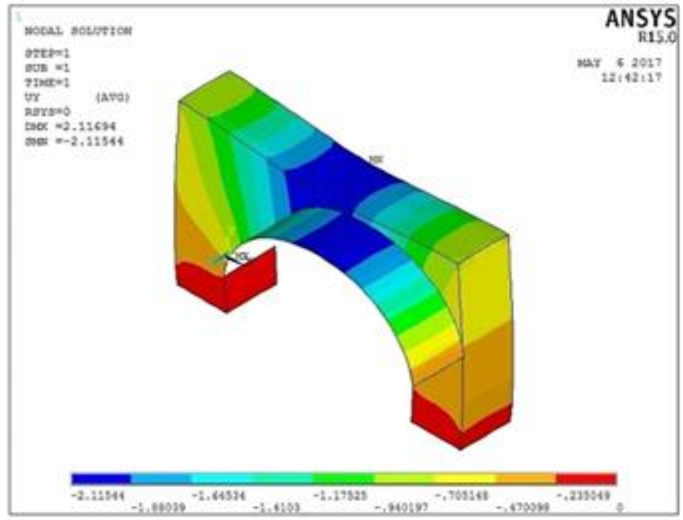

Fig. 10. Stress pattern of intrados strengthened arch.

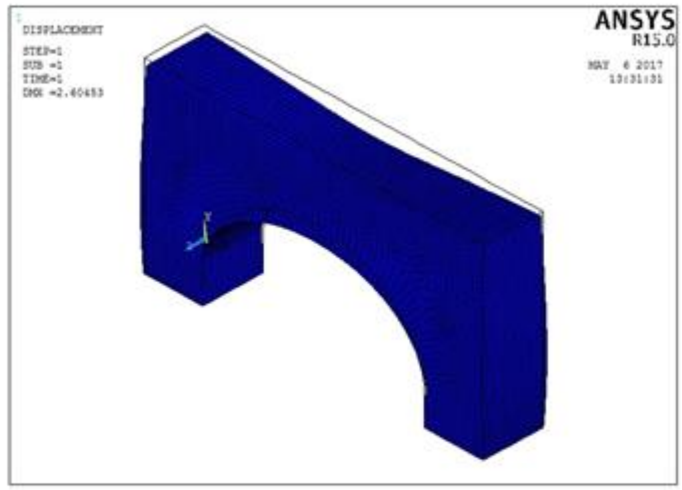

Fig. 11. Deformation shape of unstrengthened arch.

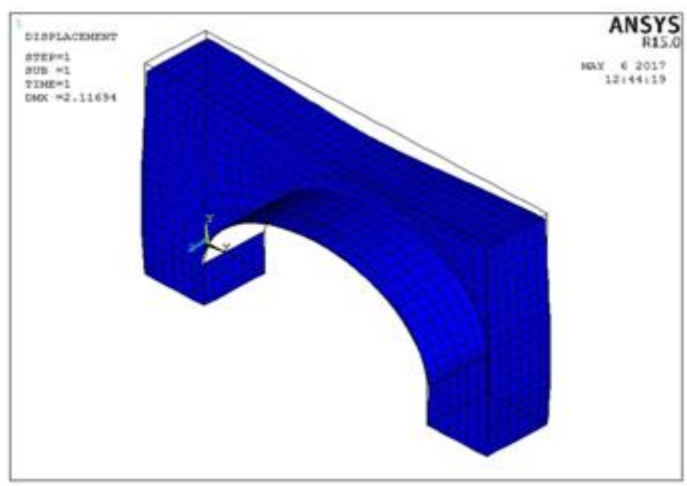

Fig. 12. Deformed shape of intrados strengthened arch.

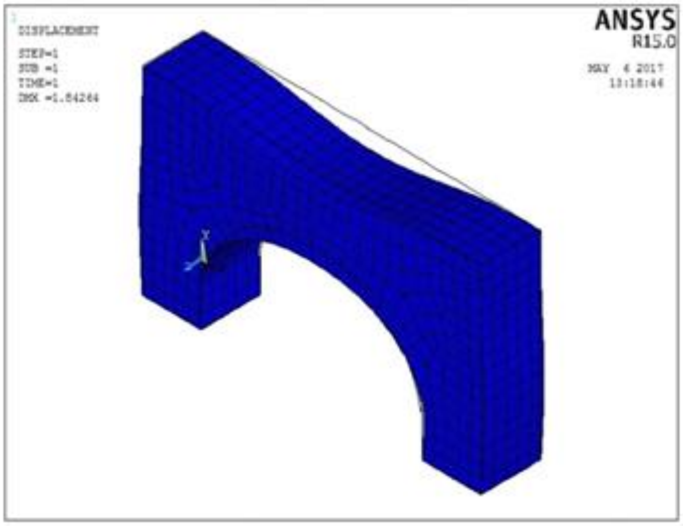

Fig. 13. Deformed shape of Extrados strengthened arch.

From the results it was observed that the experimental values for all arches were greater than analytical results. For first crack load this increment was 2 to 2.25 times than analytical results. But after first crack load the behavior of strengthened arches were different from unstrengthened arches and the difference between the experimental and analytical deflection values was also high. Previous studies also reported same kind of results [18], [19]. Sudden collapse were observed in unstrengthened arch and it was not so in strengthened arch. Because of the post cracking behavior of strengthened arch there was not much agreement found between the analytical and experimental results.

6 CONCLUSION

This Experimental work covers the structural behaviour and performance of masonry arches which were strengthened at intrados and extrados using steel reinforced grout (SRG). More precisely, the experimental work was carried out by testing the three masonry arch models in each type subjected to a uniform vertical force. This study also concerned the mechanical characterization of brick and Strengthening material (composites) by tension and compression test. Considering the arch testing, the principal parameters such as the behaviour, load-carrying capacity and maximum deflection were determined. The failure mechanisms were also detected and described accurately.

The following conclusions can be inferred from the experimental and analytical results:

1. The performance of steel mesh was better in load carrying capacity and maximum deflection for extrados and intrados application.
2. SRG composite demonstrated more effective, exclusively in case of extrados application by increasing the maximum load of 46.3 kN (more than 100% of the values of unstrengthened arch) in the case of extrados application.
3. The strengthening system increases the load carrying capacity and also prevent the cracks or the propagation of the cracks.
4. Both the extrados and intrados strengthened arches did not reach a state of collapse. Hence steel mesh effectively prevents the collapse of masonry arches subjected to ultimate stress limits.
5. SRG stands as an effective solution for strengthening of masonry arch and can be alternatively used when traditional strengthening system was limited.
6. The results obtained from the finite element analysis by considering the brick and mortar as a single material and the masonry unit as homogeneous using linear isotropic models significantly diverges from the experimental results. Hence the post cracking behaviour of strengthened arch has to be carried out to remove the difference.

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