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# A Parametric Study on Load Carrying Capacity of Backfilled Masonry Arch Bridges in Afghanistan

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## Abstract

*To be classed for accepting larger axle loads, vehicle speeds, and a growth in the amount of containerized road traffic, old masonry arch bridges must be evaluated from a fresh technical perspective and with the use of newly developed structural analysis tools. It is critical in this context to have specialist assessment methodologies due to the particular structural behaviour of these bridges, the lack of readily available data, and the trustworthiness of that data. To this end, two dimensional finite element (FE) models are developed by incorporating the detailed geometric complexities of the arch bridge with backfill. Due to lack of data in the plastic performance of the masonry material used in the arch bridges, the analysis is conducted based on the stress control method in the linear elastic method. Beside numerical models empirical approaches such as FILEV and MEXE are also used to study The technical analysis of masonry arches from a historical viewpoint will provide important knowledge for bridge retrofitting. Masonry arch bridges are mostly common in Asian Countries from old to modern types. The structural characteristic and parameters in these bridges can differ for each place due to material used for arch and aesthetic considerations of each culture; however, arch profile can be an important characteristic that effects the mechanical behaviour of bridge. This study deals with the load carrying capacity of the arched bridges of different geometric configuration with elastic material properties, and aims to determine permissible axle load for masonry bridges which are currently in use in Afghanistan transportation corridors. A wide range of arch bridges can be seen in Afghanistan. Old and new masonry bridges are currently in use in many cities for major highways. Mechanical analysis are also conducted in order to study the effect of arch profile on stress- strain behaviour of bridge. Studies in this paper is based on mechanical and physical observations from site. According to the results of the investigation, MEXE and FILEV techniques are effective approaches for estimating the safety and allowable tonnage of masonry arch bridges and have good fit with numerical and FE model results. According to FE and empirical study, masonry arch bridges with v/l arch parameter values less than 0.2 for stone masonry arch bridges and 0.42 for brick masonry bridges should not be accessible to heavy traffic (trucks with axle loads more than 10 tonnes).*

**Keywords**: Masonry Structures, Arch Bridges, stress- strain behaviour, Arch profile

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## 1 Introduction

Bridge construction is a result of the advancement and success of road construction, which has historically been one of the indicators of the wealth of civilizations. Therefore, the bridge may be regarded as an indisputable indicator in the study of civilizations of many eras, despite its architectural design and structural alterations. Because of its historical significance and unique location in social, economic, cultural, and aesthetic contexts, historical bridges can lead to essential information and knowledge for a better understanding of any nation's native engineering and architecture.

Because they conform to a few basic aesthetic principles, masonry arch bridges are regarded as beautiful. First of all, they are integrated into the landscape since they employ local construction materials [1]. Furthermore, beam bridges composed of reinforced or prestressed concrete are frequently perceived as strange, in contrast to the brilliant notion of arranging stones or bricks geometrically such that the mechanical qualities of bricks and stones are employed in a nearly perfect way. Old masonry arch bridges need to be reassessed from a new technical perspective and with the aid of the recently available structural analysis methods in order to be reclassified for accommodating higher axle loads, vehicle speeds, and an increase in the volume of containerized road traffic. Due to the unique structural behavior of these bridges, the dearth of accessible data, and the dependability of that data, it is vital in this context to have specialized evaluation methods. The historical perspective on technical examination of masonry arches gave important information for bridge retrofitting[2, 3].

Arches are mostly common in Asian architecture, and can be widely seen in historical and modern structures. Brick masonry arch is a major structural element which is used in Asian architecture especially in Iran and Afghanistan. This structural element is mostly used to cover long span halls and bridges. Malaan Bridge in Heart, old Guzargah Bridge in Kabul Si-o-se Pol and Khuajo Bridge in Isfehan can be good examples of brick arches used for bridges. On the basis of construction material, masonry arch bridges may be devided into three groups: brickwork arch; stone arch bridges and plain concrete arch bridges. On the other hand, stone arches and stone arch bridges can be mostly seen in European and Chinese architecture. In the $20^{th}$ century some arch bridges were built in Afghanistan in European style using stone masonry arches. Horton Bridge in Kabul city can be a good example of stone masonry bridges in Afghanistan. Stone masonry bridges were mostly developed and used in Iran for railway corridors in past 70 years which Versek arch bridge is a good example. Mostly, these masonry bridges were built for light weight vehicles or chariots; however, some of these structures are open to daily traffic after some rehabilitation, reinforcing or reconstruction. For instance, Malaan Bridge in Herat was reconstructed using its ancient design after structure was highly damaged in war. The masonry part of Pol-e-Sokhta Bridge in Kabul city is also open to daily traffic.



Figure 1 Brick and stone masonry arch bridges in Afghanistan

In order to determine the load bearing capacity of the masonry arch bridges many different ways are being used. Which are: Empirical Rules, Beam models, FEM (Finite Element Models), DEM (Discrete element models), and experimental models. For the simplicity of the process many modern rules such as MEXE ((Military Engineering Experimental Establishment) [4], FILEV Method by Martín-Caro and Martínez[5], Method by Harvey et al.[6] Method by Purtak et al.[7] Method by Martinez et al. [8], Method by Aita et al. [9]Method of Pauser[10] are developed.

FEM is a powerful tool for the analysis of the engineering structures and it gives us the opportunity to study the behaviour of bridge in various scenarios. This paper aims to determine the permissible vehicle tonnage for these masonry bridges using elastic models which are developed using FEM method in commercial ABAQUS software. Due to a lack of data on the plastic performance of the masonry material used in arch bridges, the study is based on the linear elastic stress control approach. The elastic approaches provide comparable information in the stress concentration zones, and because they are less time demanding, we may test a wider range of geometric parameters.

## 2 Methodology

To accomplish the aforementioned objectives several FEM models and Empirical methods are utilized which are: MEXE method, FILEV Method, and FEM method. Some short descriptions on the above methods are provided as following:

### 2.1 Empirical Methods for Investigating Masonry Bridge Load Carrying

#### 2.1.1 MEXE Method

The British Ministry of Supply sought to classify the bridges according to what military weights they could take, thus they devised the semi-empirical MEXE system during the Second World War and into the 1950s. The technique was created using a variety of full-scale experiments and mathematical computations, and it is reliable under the following presumptions [4]: The load was applied as a point load in the crown, the arch is parabolic,

two-pinned, and in fine condition; The depth of the fill lies between 30-105 cm in the arch crown; • The span is less than 20 m; The rise at the crown is greater than one-fourth of the span;

Thorough the tests and calculations, diagrams for the relations between the span L, the depth of the fill above crown h, the thickness at the crown d, and the provisional axle load (PAL) were created. Later the diagrams were replaced with the eq. 1.

$$PAL = \frac{740(d+h)^2}{L^{1.3}} \tag{1}$$

The provisional axle load is the multiplied with the following five factors:

$$f = f_S\, f_M\, f_J\, f_C\, f_N \left(\frac{1}{f_\varphi}\right) \tag{2}$$

In which $f_S$ is the shape factor; $f_M$ is the material factor; $f_J$ is the joint factor; $f_c$ is the cracks factor; $f_N$ is the factor of the number of arches;

#### 2.1.2 Explicit formula for calculating ultimate load by Martín-Caro and Martínez

For the almost 800 bridge models with various parameters Based on the multivariable regression analysis used in Martn-Caro and Martnez's [5] FILEV approach, the ultimate load bearing was examined using the FE software Sofistic. The Following formula in eq. (3) is suggested to predict the permissible load for masonry arch bridges by Martn-Caro and Martnez's:

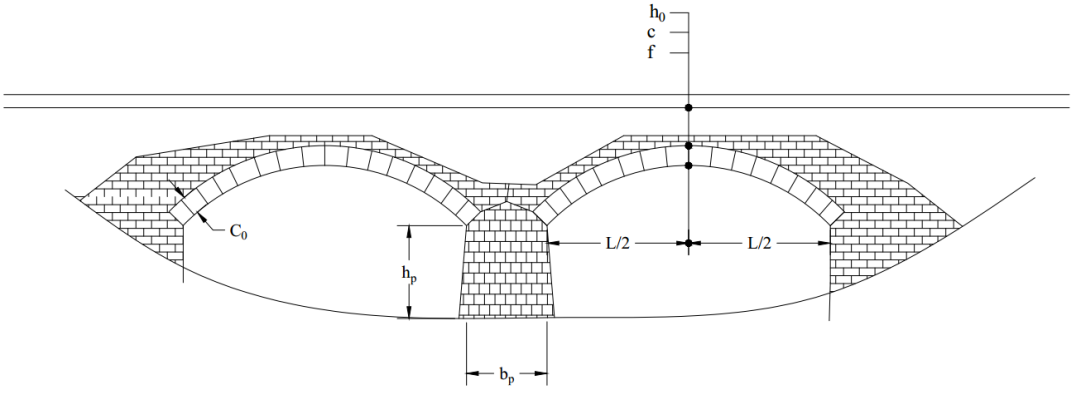



Figure 2 Arch Bridge Parameters

$$P_{ult} = (AL^2 + BL + C)K_1K_2 \tag{3}$$

$$K_1 = \begin{cases} 1 - 0.05\left(\frac{L}{f} - 4\right)^2 & if\ \frac{f}{L} \le 0.25\ \ and \frac{h_P}{L} > \frac{1}{2} \\ 1 + 0.03\left(\frac{L}{f} - 2\right)^2 & else \end{cases} \quad (4)$$

$$K_2 = 1 + \left(\frac{h_0}{2.5}\right)^2 \quad (5)$$

## 2.2 Finite Element Method

As commonly encountered in practice, the arch bridges with different types of f/l value are of interest, that is, two sets of bridge models are developed in ABAQUS [11] with stone and brick arches .A set of lorry vehicles are used for static response analysis, and the comparison study is done in 8 bridge models for stone bridges and 8 for brick arch bridges. The main parameter for study is arch profile based on f/l in which: f is the arch height and l is the span length. The vehicle set is used from Euro code EN 1991-2 [12]. A 2D FE model is used in ABAQUS Implicit analysis, the loading set is introduced to the model using DLOAD subroutine {Smith, 2009 #21}. The analysis procedure is described in the Figure 4 The boundary and load condition of the model is illustrated in Figure 3.

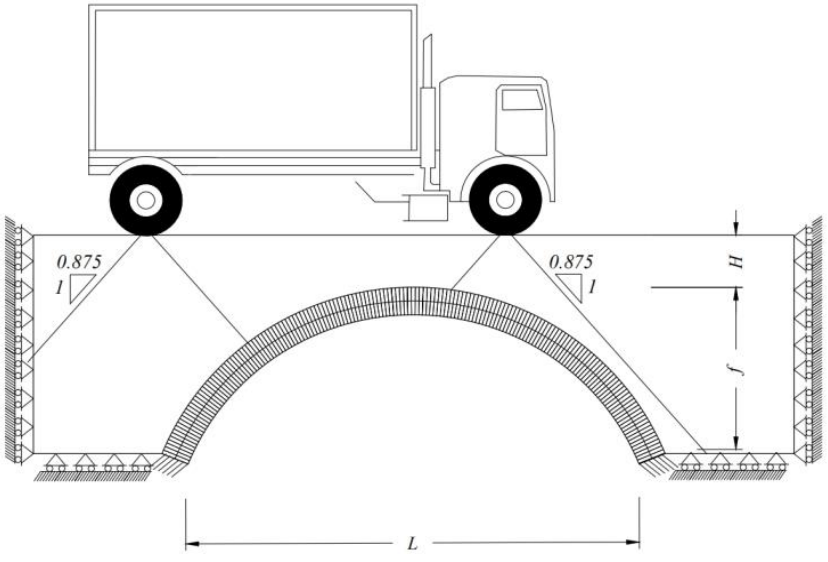



Figure 3 FEM boundary condition

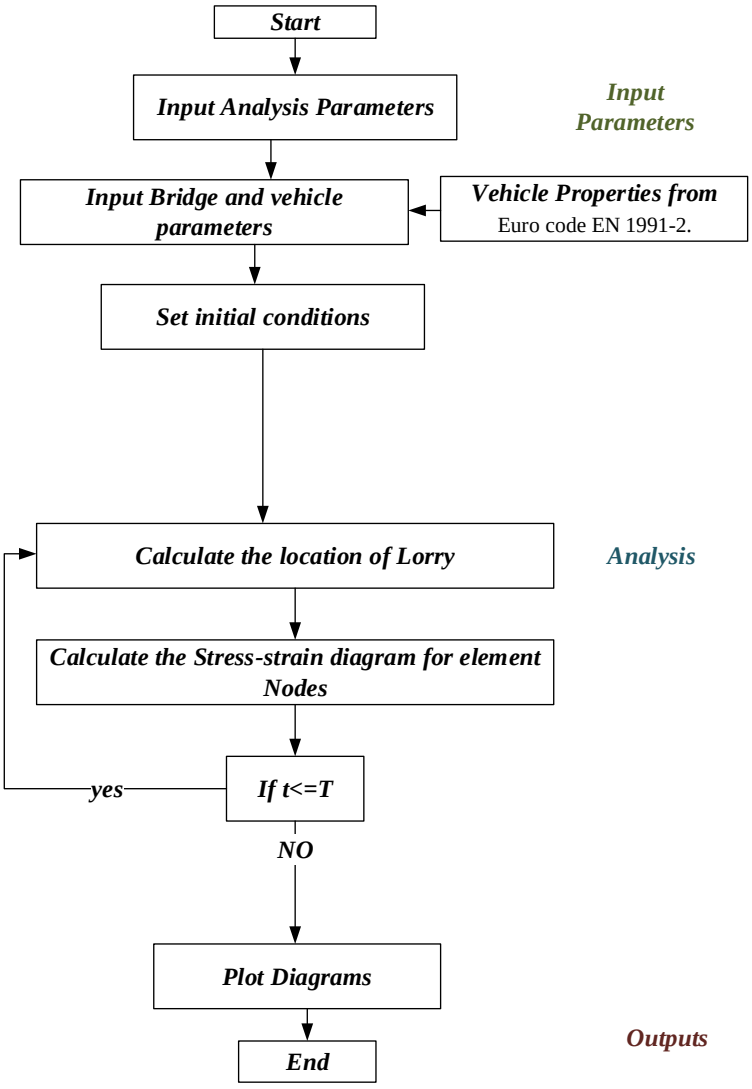



Figure 4 FE Analysis flowchart

### 2.2.1 Bridge Models

Two sets of bridge models were developed which were: stone masonry bridges with fl/l from 1/2 to 1/ 7.5; brick masonry arch bridges with f/l from 1/2 to 1/7.5. Bridge span lengths are given in Figure 6. The width of bridge is 8m with 2 traffic lane. In the numerical model both lanes is loaded by traffic lorry loads. The material specifications for stone and brick arches are given as bellow in tables. The FEM model established in ABAQUS is illustrated in fig. The stress and displacement data is collected for the control points as shown in Figure 7.

Table 1 Bridge FEM model Properties

| Bridge | Compressive Strength (MPa) | Elasticity modulus (GPa) | Poisson Ratio | Density ($Kg/m^3$) |
|---|---|---|---|---|
| Stone Arch | 21 | 17.1 | 0.29 | 2270 |
| Brick Arch | 2.6 | 2.72 | 0.213 | 2050 |

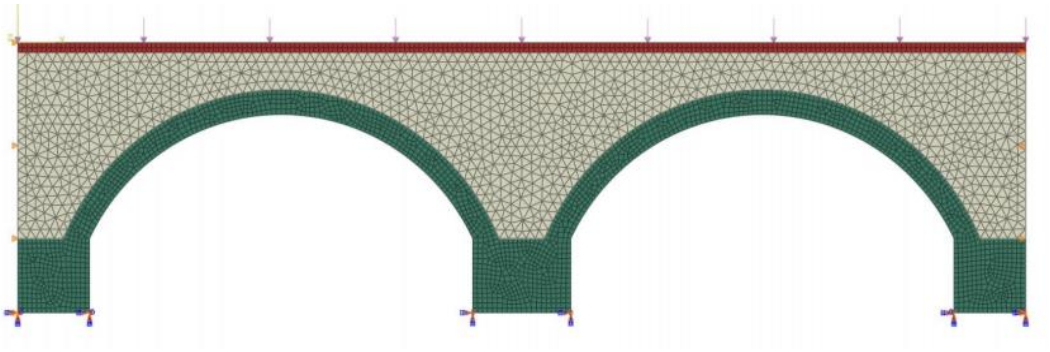


Figure 5 FEM model in ABAQUS

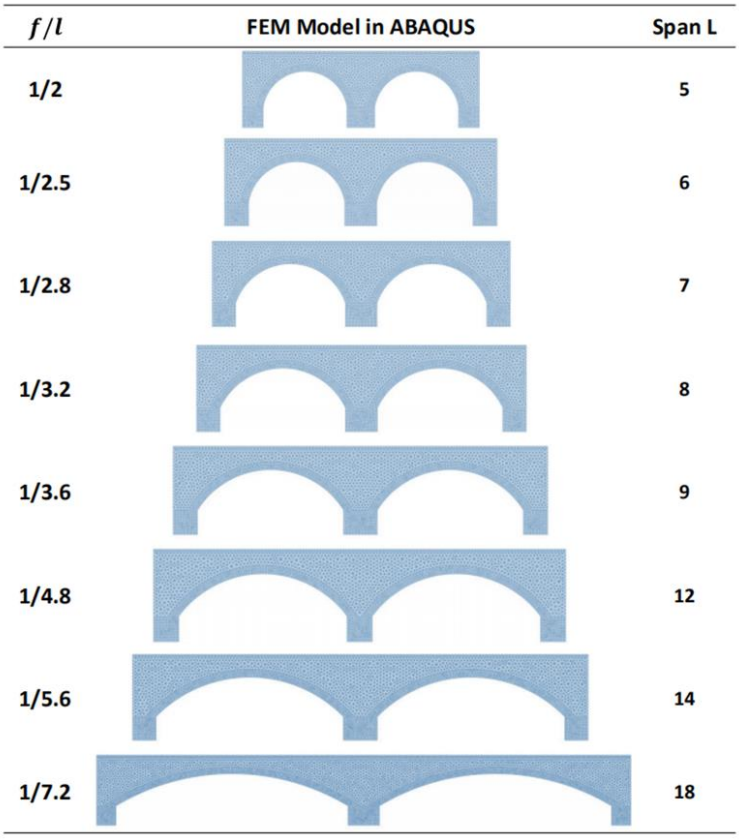



Figure 6 FE Bridge models

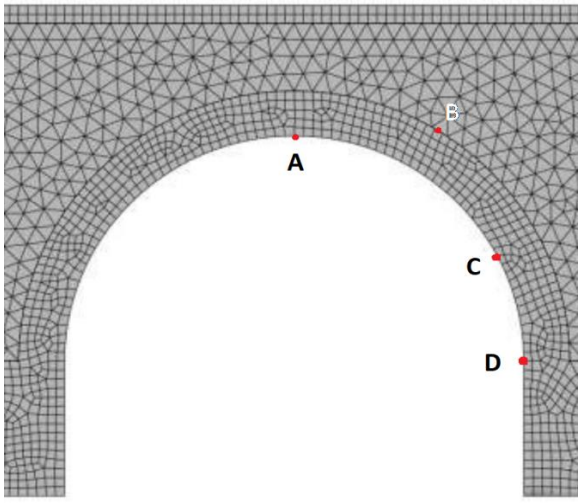



Figure 7 FE models control points

### 2.2.2 Load conditions

Static response analysis is performed using a set of lorry trucks, and comparative studies are completed using 8 bridge models for stone bridges and 8 for brick arch bridges. Arch profile based on f/l, where f is arch height and l is span length, is the primary research parameter. The vehicle set is taken from Euro code EN 1991-2 [12], and Figure 8 show the geometric definition of the vehicle and the load parameters.

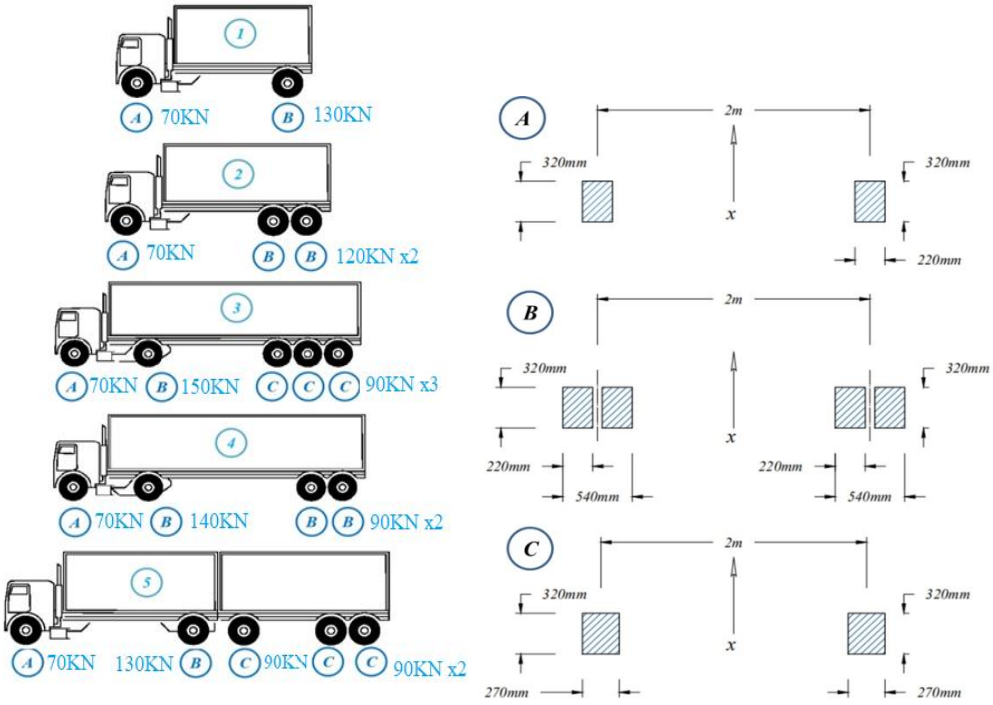
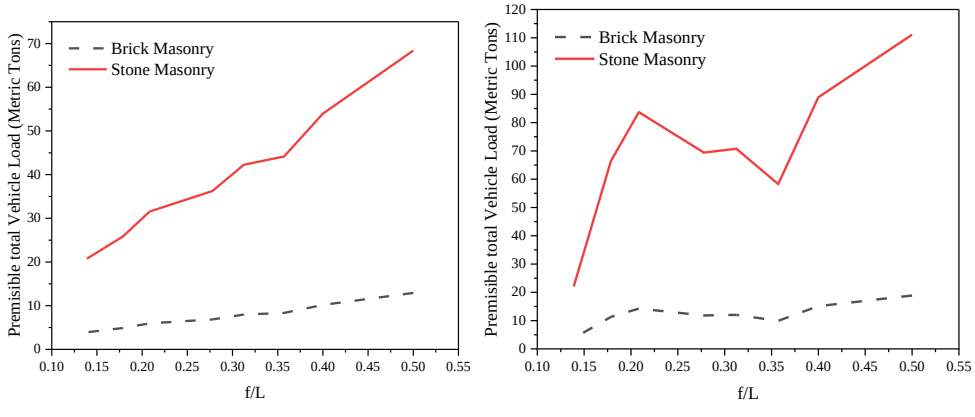



Figure 8 Lorry set Geometric and axle information

## RESULTS AND DISCUSSIONS

Using MEXE and FILEV empirical models, one can observe as illustrated in Figure 11 that for smaller f/l values we have very less permissible tonnage. Based on the findings from the empirical models, we can state that the brick masonry arch bridges are extremely dangerous heavy trucks in f/l values less than 0.4, and this statement is true for f/l values smaller than 0.2 for stone arch bridges.



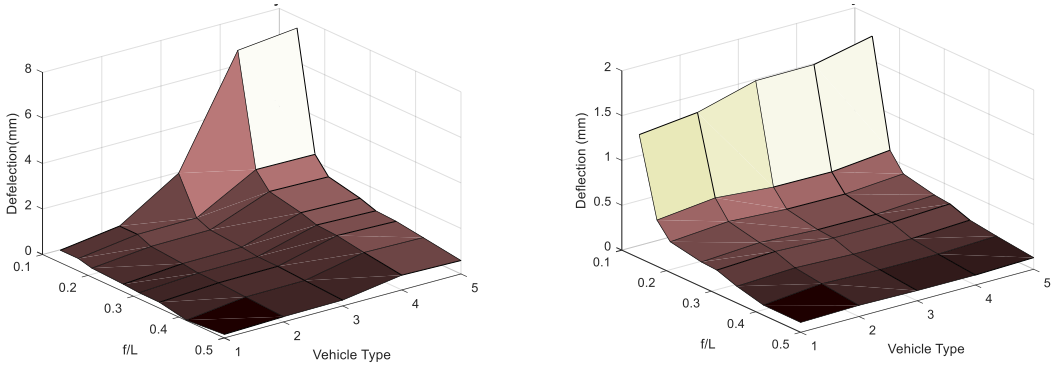

(a) MEXE Method

(b) FILEV Method

Figure 9 Permissible tonnage according to empirical models

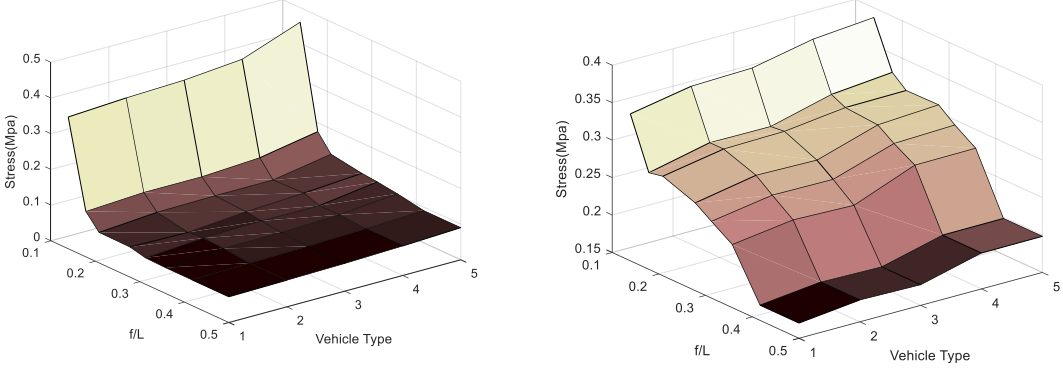
Based on the FE analysis, in which used a set of lorry vehicles for static response analysis, and the comparison study is done in 8 bridge models for stone bridges and 8 for brick arch bridges. The main parameter for study is arch profile based on f/l in which: f is the arch height and l is the span length.

The results derived from FE analysis are presented as following can be divided in two parts: For stone arches, as illustrated in Figure 12 and 13 , it can be observed that for f/l less than 0.2 stresses and displacements can rise, and is not suitable for heavy traffic. The same observation can be seen for brick arch bridges as well, which higher displacements and stresses are observed for f/l less than 0.42.

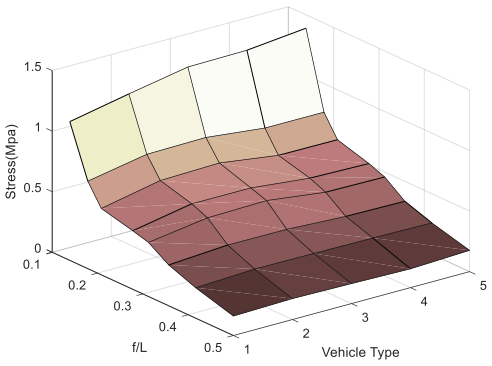



(a) Stone Masonry (b) Brick Masonry

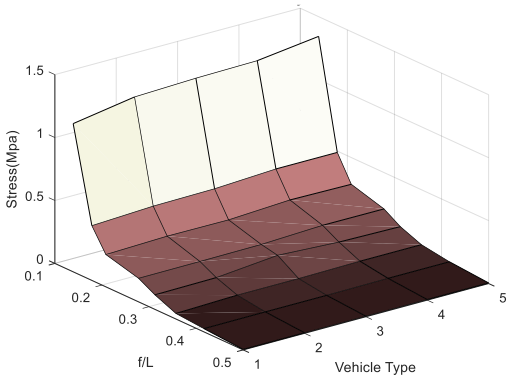
Figure 10 FEM Displacement response data results



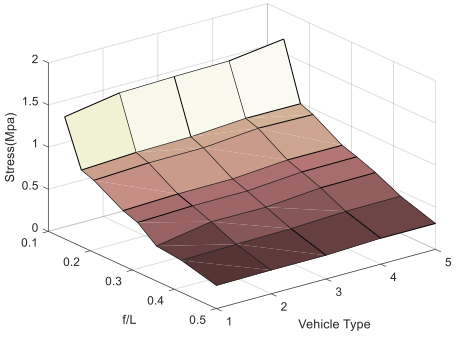

(a) Stone Masonry (b) Brick masonry




(c) Stone Masonry




(d) Brick Masonry




(e) Brick Masonry

Figure 11 FEM stress response data results

## 3 Conclusion

As observed in the analysis, computerized MEXE and FILEV methods are good tools for determining the safety and permissible tonnage of masonry arch bridges and have good adaptation with numerical and FE model results. MEXE and FILEV methods can be very cost-effective and time saving for official and field matters. Due to findings on the Finite element study following terms are suggested for masonry arch bridges operating under heavy axle loading.

Stone Masonry Arch Bridges:

F/l less than 0.2 should not be open for heavy traffic

F/l higher than 0.2 should be open to truck traffic not heavier than 10 ton axle loading

Brick Masonry Arch Bridges:

F/l less than 0.42 should not be open for heavy traffic

F/l higher than 0.42 should be open to truck traffic not heavier than 10 ton axle loading

For increasing reliability and safe operation of masonry arch bridges, normal monitoring,

and maintenance should be accomplished for old masonry bridges which are currently in use. To develop more accurate models for masonry arch bridges, further experimental studies on the construction methods, and material mechanical properties should be done on the masonry bridges in Afghanistan.

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