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DYNAMIC ANALYSIS OF MASONRY VAULTS UNDER EARTHQUAKE LOAD USING GENETIC PROGRAMMING

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Abstract. *Genetic Programming (GP) is a developed method based on the Genetic Algorithm for optimization. This method involves computer programs. It is believed that, the geometry of a structure and the configurations of the vertical and lateral load bearing systems have essential roles in structural stability, during catastrophic events in their lifetimes, such as, earthquakes. This study focuses on the optimum shape of the masonry semicircular vaults and considers the vaults dynamic response against the El Centro earthquake (1940) in conducting the Genetic Programming.*

In this paper, different form of vaults in heritage and historic structures have been studied. The GP goal function, for minimizing the weight of the vault, has been defined by considering the important parameters in the structural dynamic response of the vaults, such as, the base and the top thickness, the vaults radius and the maximum tensile stress. After developing the first population of the vaults, the genetic operators (generation, crossover, mutation, etc.) have been utilized by a C^{++} program, so as to upgrade the vaults shape and produce a better population of the shape of vaults.

A group of vaults consisted of 100 samples, were studied by this method. Finally, the optimum ones were determined. This method has tested by reproducing the other 100 samples of vaults and calculating the error for each model. The output showed the efficiency of the algorithm as to the analysis, design and the optimized shape of the vaults under dynamic loads, using the radius and base thickness of the vault as the input parameters. The top thickness and maximum tensile stress of the vault could be estimated by the software.

Ultimately, it was revealed that, first: optimal shape and dimension of a historical vault is one of the important advantages which cause it exist during the history and second: the prepared program is an efficient tool, which is capable of being developed, based on the desired earthquake time history, as well as being utilized for interpreting the role of the geometry of masonry vaults, in relative to their vulnerability or stability against that earthquake.

1 INTRODUCTION

Traditionally, a vault is defined as a part of circle or bow, but a particular definition of vault is as follows: it is a curved surface for covering, that its span is higher than its depth [1].

Among the structural components in masonry buildings, arches and vaults deserve particular attention. They are very widespread in historical centers and their preservation as part of the cultural heritage is a very topical subject. Because of their ages or foe accidental causes (such as earthquakes), these structures can undergo several types of damages.

The increasing interest in historic architectural heritage and the need for the conservation of historical structure has led to the continuous development of many methods for the analysis of masonry vaults. However, some types of vaults have not been thoroughly analyzed, mainly because of the problem of applying simplified theories to their complicated shapes [2]. This paper, focuses on the stability and strength of vaults Fig. 1, shows the ruins of Ctesiphon in Iraq. The optimal shape of the vault cause it survives more than 2000 years.

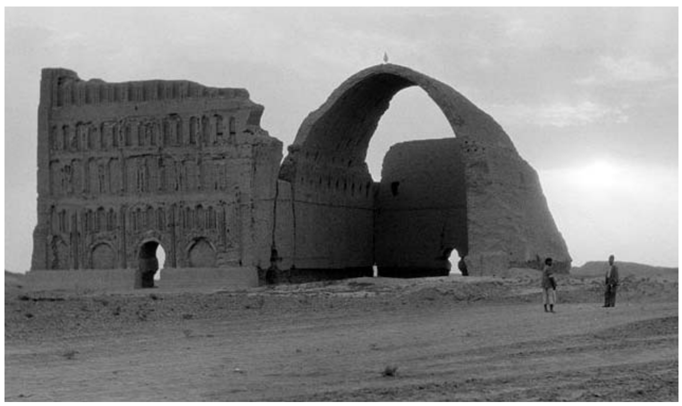

Figure 1: Ruins of Ctesiphon, Iraq

There has been some research performed on brick masonry under dynamic loads [3]. Dynamic or time history analysis is an analytical method for determining response of structures during earthquakes. For dynamic analysis and optimization of vaults a lengthy period of time is needed. It is necessary to use a proper computational model such as genetic programming to analyze and optimize the vault in less period of time and for more acceptable results too [4]. Nevertheless, it is generally difficult, if not impossible, to identify the characteristic(s) that make a rule produce a particular pattern. Discovering rules that produce spatial patterns that a human being would find "similar" to another given pattern is a very important task, having given its numerous possible applications in many complex systems models [5].The main importance of this research is to show the ability of analyzing and optimizing of every vault after a period of modeling in a much shorter time.

2 MODELING, ANALYZING AND OPTIMIZING VAULT SHAPE USING FEM SOFTWARE

The vault modeling has been conducted in detail by the FEM software. Furthermore, dynamic analysis has been conducted and the north-south horizontal component of Elcentro earthquake in which the duration, maximum acceleration, maximum velocity and maximum displacement are 31.98(s), 0.31(g), 33 (cm/sec) and 21.4 (cm) were applied. Vault shape optimization emphasized on the minimizing of vault weight. In FEM software, the base and top thickness, maximum tensile stress and weight of structure have been defined as design variable, state variable and objective function, respectively. For example, the optimum shape of semicircular vault in FEM software has been shown in Fig.2. Regarding the extra time for analysis and optimization, the optimization has been conducted in design optimum processor by means of the Sub Problem Approximation Method. This is an estimation method for variable designing, state and objective function via curve fitting tool. It is a general method for solving many engineering problems [6].

In all models, the base thickness, top thickness, radius and length of vault are considered 0.8 to 1.44, 0.2 to 0.35, 4.5 to 6 and 1m, respectively. Then using the FEM software, the time history analysis was performed for modeled vaults to determine maximum tensile stress. Assumed permissible tensile stress in masonry was 50000N/m^2. In vault analysis, it is necessary to provide the optimum maximum tensile stress in top and base thickness.

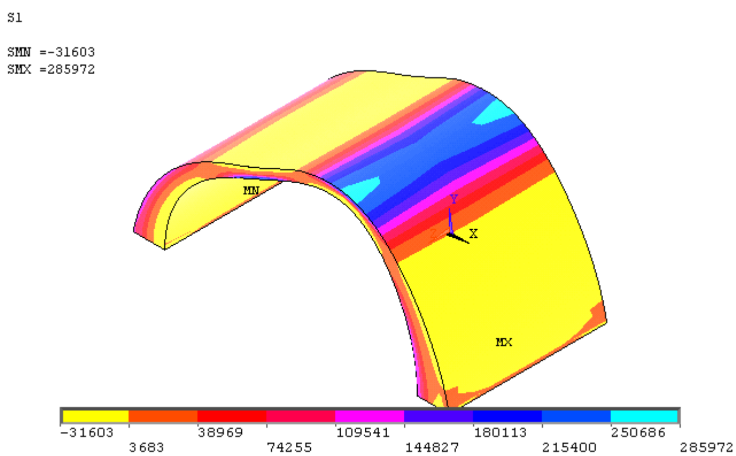

Figure 2: Optimum shape of semicircular vault using FEM software

Using C^{++} program, 100 data for vault maximum tensile stress obtained by the FEM software are considered. Then other 100 samples were chosen as a secondary population which were analyzed by the FEM software and the error percent were calculated by comparing the maximum tensile stress in secondary population and the best GP model.

2.1 Geometrical modeling

According to shape optimization design variables, such as base thickness (t_0) and top thickness (t_1) as parameters, all the key points are defined in Fig.3:

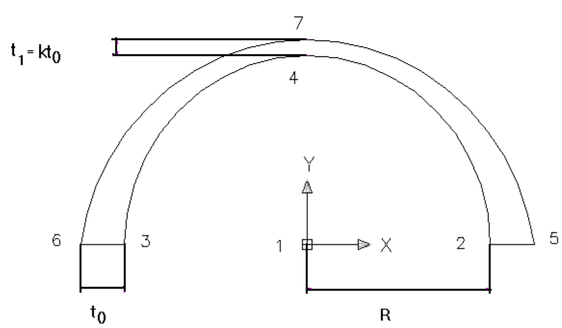

Figure 3: Key points coordinates

Point1 (0, 0); Point 2 (R, 0); Point3 (-R, 0); Pint4 (0, R); Point 5 (R+t_0, 0); Point 6 (-R-t_0, 0); Point 7 (0, R+t_1)

In vault modeling, the tolerance increases because the thickness decreases from base to top [7]. It should mention that in a modeled vault, the thickness decreases from base (t_0) to top (t_1) linearly and the vault thickness of axis is 20 (cm) in the length direction. The motion of support nodes is zero and dynamic force has no effect on them. In addition, brick masonry is made by brick and mortar as homogenous material (Table1). The important parameters in the inelastic nonlinear analysis have been shown in Table 2. In the present paper, vault radius limit (R), maximum tensile stress, base and top thickness in optimum state are considered as 4-8 (m), 49000-5100 (KN/m^3), 0.8- 1.44 (m) and 0.2-0.35(m) respectively for all modeled vault.

Table1: Brick masonry characteristics [7]

density(ρ) Kg/m^2	Elastic modulus N/m^2	Allowable tension stress(f_t)	Poisson ratio (υ)
1460	5×10^8	0.5×10^5	0.17

Table 2: Effective coefficient in non-elastic and nonlinear analysis [8]

motion coefficient for open crack	motion coefficient for close crack	Allowable tension stress N/m^2	allowable compressive stress N/m^2
0.1	0.9	5×10^4	5×10^5

2.2 Genetic programming

Genetic programming (GP) is obtained from Darwin Evolutionary Theory in which, there is a primary population. In GP, tree structures are used using mathematical sentences which is shown in Fig. 4.

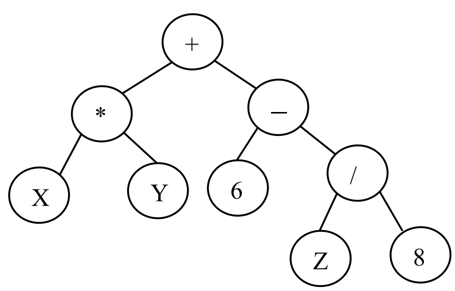

Figure.4: Tree structure of GP: (X*Y) + 6 - (Z/8)

According to this figure, the following steps are necessary:

1- Some of rules are chosen as primary population.
2- Provided rules are valued using fitting function.
3- Some of rules are selected by the valuing system in the reproduction mechanism.
4- Crossing operators, reproduction and mutation operators are used to provide new rules.
5- New generation are used to provide new population.
6- Steps 3 to 6 are repeated until a suitable classification rule is provided.
7- Steps 2 to 7 are repeated until a suitable rule is obtained for groups provided in data collection.
8- In training and experimental collection, each sample belongs to a special group.

The next step is the application of the GP algorithm itself. A basic representation of the algorithm is presented in Fig.5.

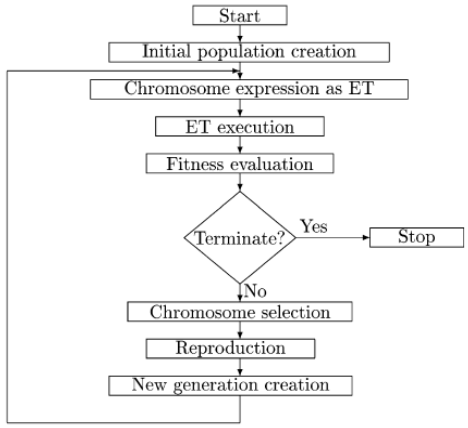

Figure 5: Basic GP algorithm

2.3 Vault analysis using GP

We are going to exploit the GP approach introduced in [9]. In this stage, regarding the definition of GP, the data for each vault will be analyzed to find the simulation models of each vault behavior. To achieve this aim, 100 samples of each vault radius, base and top thickness and maximum tensile stress were chosen and analyzed by the FEM software. The error percent of the model were determined. Semi-circular, obtuse angle, four- centered pointed, Tudor, ogee, equilateral, catenaries, lancet and four-centered vaults were analyzed and the results determined. Sample GP data, concept and results for Semicircular vault modeling are shown in Fig. 6 to 8.

Generation	Program Size	Literals	Used Variables	Training Fitness	Testing Fitness	Training R-square	Testing R-square
4361	25	6	Base(2), Radius(1), Top (3)	872.414329457005	--	0.978707804917376	--

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GOE3D.GOE3D.GOE3D.c0.c0.c3.d2.c2.c0.c3.c0.d2.c0
-
/.Floor.Coth.d2.d2.d1.d2.d0.c4.d0.c3.d1.d2
-
NET4H.GOE3L.GOE2F.c3.c4.c1.d0.d0.d1.c0.d1.d0.c2

Numerical Constants:

Gene 1
c0 = 9.268554
c1 = 4.104766
c2 = 8.028472
c3 = 1.367767
c4 = -5.113311

Gene 2
c0 = 9.268554
c1 = 1.914856
c2 = 8.328094
c3 = 3.042358
c4 = -9.06311

Gene 3
c0 = 4.380493
c1 = 0.256653
c2 = 7.203674
c3 = 2.172424
c4 = -3.144378
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Figure 6: Specific data produced by GP concepts for Semicircular vault modeling

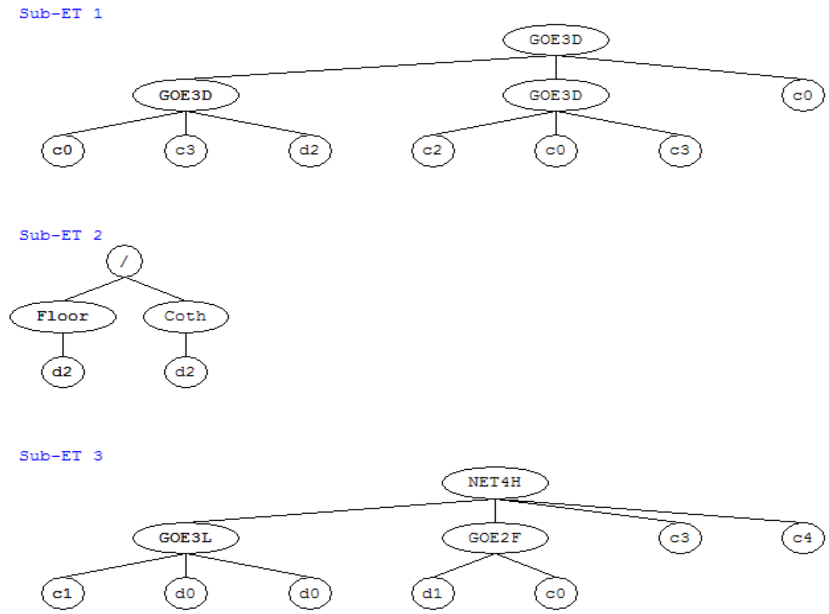


Figure 7: ETs for Semicircular vault modeling based on GP operators

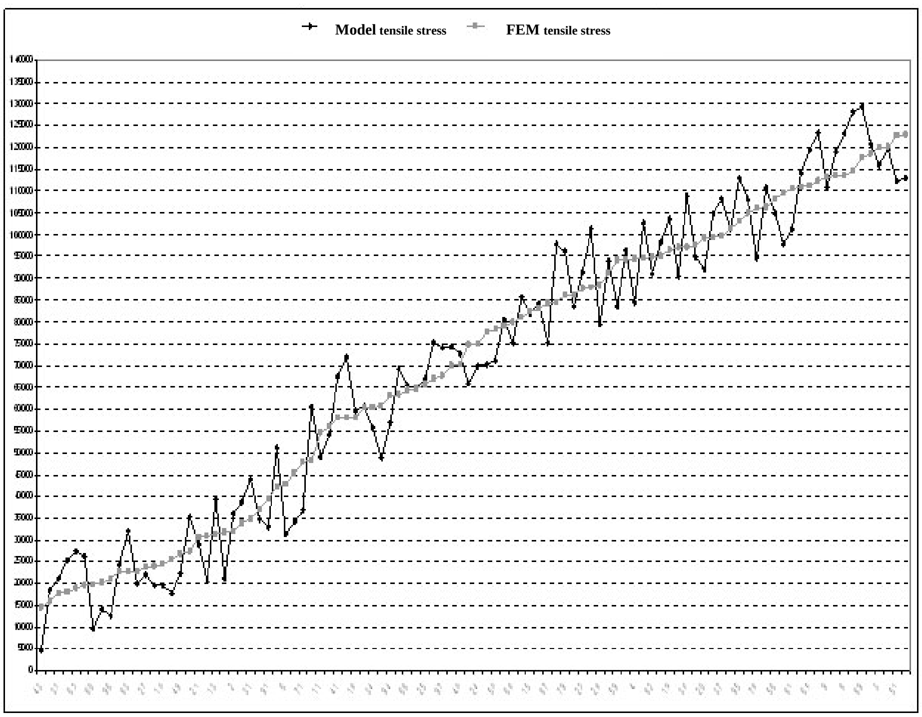


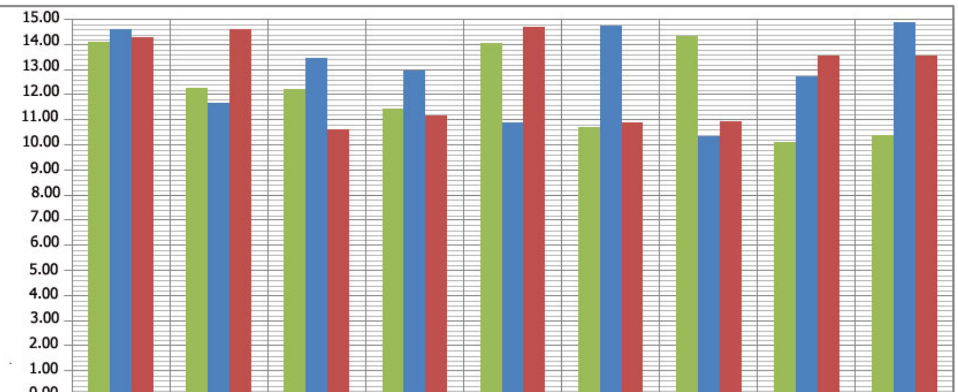
Figure 8: Comparison between the mean of error percent of analysis of tensile stress using FEM and GP in semi circular vault

3 CONCLUSION

In the present paper, nine types of arches including: semi-circular, obtuse angle, four- centered pointed; Tudor, ogee, equilateral, catenaries, lancet and four-centered arches were modeled using the FEM software and GP.

In considering the results, the GP model can be used in simulation of all vaults. Therefore, the time of calculation decreases. Also, it can be used under different dynamic loads and in various types of problems of natural frequency and response of structures. To increase GP models precision, one can increase the number of Chromosomes which are larger than 30 and a repetition of more than 1000000 times is required. The results of the above mentioned technics in this study are summarized in Fig.9.

This tool could be utilized find the optimum shape of the vaults and could be conducted to vindicate the stability of some vaults during the history.



	catenary	equilateral	four- centered pointed	four- centered	lancet	ogee	obtuse angel	semi-circular	Tudor
Base Thickness Error Percent AVG	14.12	12.31	12.27	11.45	14.07	10.71	14.38	10.14	10.42
Tensile Stress Error Percent AVG	14.62	11.71	13.47	12.99	10.90	14.78	10.37	12.75	14.91
Top Thickness Error Percent AVG	14.32	14.64	10.65	11.18	14.71	10.92	10.98	13.60	13.57

Figure 9: Comparison between the average of error percent of analysis of tensile stress, optimization of base and top thickness for various type for vaults using FEM and GP model

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