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Optimum Sections of Steel Single-Layer Barrel Vaults Using Genetic Algorithms

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1. Abstract

This paper studies the optimization problem of single-layer steel barrel vaults as a type of space frame under the effects of self-weight and earthquake loads. ***Genetic Algorithms*** were used to find the optimum sections of the structure. The minimization considered the weight of the structure as an objective function and the design variables were the cross-section area of the members. Suitable sections from standard section lists of the American Institute of Steel Construction (AISC) were selected throughout the optimization process. Strength and displacement constraints were formulated according to the American Institute of Steel Construction-Load and Resistance Factor Design (AISC-LRFD). The weight of the barrel vaults increases with the increase of the depth to span ratio after 0.2. The barrel vaults with a depth to span ratio of 0.2 has the greater reduction in weight for the three studied cases (pipe, box, and angle sections) so the ratio of 0.2 present the optimum case. The barrel vaults with box sections have an optimum than the other section shapes (about 20.4% of that of the pipe section and 13.6% of that of the angle section). The Pipe section is not economic to use in this type of barrel vault.

2. Introduction

The braced barrel vault is a space frame composed of members arranged on a cylindrical surface. It is one of the oldest ancient architectural structural forms, used to cover large areas. The old barrel vaults were constructed using masonry units, while, the modern is constructed mainly from aluminum and steel so that the total weight of the structure is much less than the old one and the cost of construction is lower [1]. In the nineteenth century, there was a great improvement, as steel supports were added to resist the horizontal forces generated in the structure. The main stresses in a barrel vault are axial stresses with minor bending stresses at the intersections between the members. Barrel vaults are taking the form of a cylinder, semicircular, parabola, ellipsoid covering circular or polygonal areas.

The optimum design of braced barrel vault has been studied by many researchers. **Sayali Jadhav (2019) [4]** studied the behaviors of four types of double-layer steel braced barrel vaults. The four types were compared based on axial force and deflection for the top layer and the optimum geometry was determined. Finite element software STAAD-PRO was used for modeling and analysis. The result shows the square on square and latticed truss types was the optimum. **A. Kaveh et al. (2012) [5]** explained an algorithm to find the optimum design of a steel barrel vault. Charged System Search (CSS) method was used for optimization. This algorithm method was more efficient compared with another meta-heuristic algorithm. The minimization was done by weight. Stress and displacement constraints were formulated according to the American Institute of Steel Construction – Load and Resistance Factor Design (AISC-LRFD). **Osman Tunca and Ibrahim Aydogdu [6]** studied the optimum design of a braced barrel vault system using a cold-formed steel section. Bee colony algorithm and an application programming interface (API) have been proposed to find the optimal design of a double-layer braced barrel vault.

3. Types of steel single layer braced barrel vaults

There are many types of bracing that can be used in the construction of single-layer braced barrel vaults but only five types can be considered as the most used ones in practice.

Figure (1) shows the types of bracing barrel vault and they are as follows: -

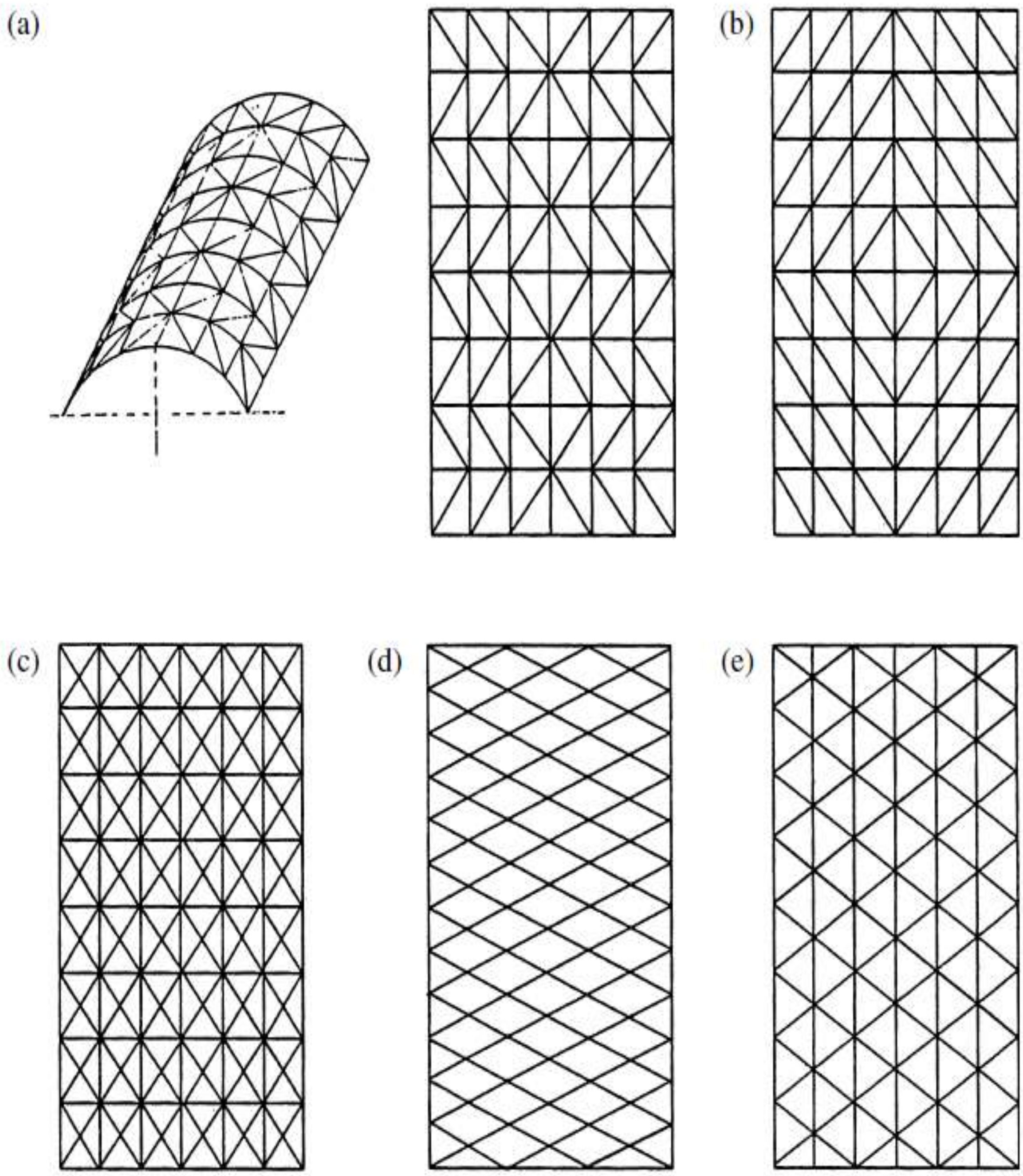
1. Orthogonal grid with single bracing of Warren truss (a).
2. Orthogonal grid with single bracing of Pratt truss (b).
3. Orthogonal grid with double bracing (c).
4. Lamella (d).
5. Three-way (e).

Orthogonal grid with single bracing of Warren truss and Orthogonal grid with single bracing of Pratt truss and Orthogonal grid with double bracing can formation it using composing latticed trusses with a different arrangement of bracings. Floppy was introduced to the original barrel vault which consists of several latticed trusses stretched along the barrel and supporting on the gables.

Lamella Braced barrel vault type can be formed by several interconnected members units forming a rhombus-shaped grid pattern like a diamond. Each unit; has twice the length of the side of a diamond, which calls a lamella. Because all the units have standard sizes, lamella roofs are suitable for prefabricated construction. The old one was formed from timber, but the modern one from steel due to the increase in span.

A three-way grid braced barrel vault is formed by a system using equilateral triangles, which have the same length and are connected with simple nodes. The analysis of these braced barrel vaults showed a very uniform stress distribution under uniformly distributed loads and unsymmetrical loads the deflections were much smaller than the other type of braced barrel vaults.

Figure (1) Types of Braced Barrel Vaults



4. Optimization

Optimization is the process of finding the best outcomes for any preassigned circumstances. In the process and activities of any system, managerial and technological decisions must be taken by engineers at many stages. Minimizing the effort necessitated or maximizing the demanded profit are the reasons behind all such decisions. Since the benefit desired or the effort required in any practical situation can be introduced in the form of a function of several decision variables, optimization might be defined as the process of exploring the circumstances that generate the minimum or maximum magnitude of a function [7].

For a general optimization problem, a proper representation of an objective function, design variables, and constraints at the problem formulation state is required. According to the type of problems and requirements, several types of objective functions and design variables can be represented.

5. Genetic Algorithms

Genetic algorithms are random search methods that simulate some processes of natural biological evolution. The main reason for using genetic algorithms is to get the optimization. Genetic algorithms work on a set of potential solutions based on the "***survival of the fittest***" principle to generate better and better approximations of a solution. In each generation, a new population is created by the process of breeding individuals according to their correspondence fitness value in the problem area and their upbringing together using factors taken from natural genetics. This procedure leads to the development of individuals more adapted to their environment than the individuals from which they were bred. GAs model natural processes inspired by natural adaptation such as **selection**, **crossover**, and **mutation**. Figure (2) represents the structure of a simple genetic algorithm. In Gas, research is carried out in a parallel manner. The number of individuals is used instead of a single solution. Several individuals (population) are randomly configured to choose a so-called gene set or mating set at the start of the calculation. For each of these individuals (also called strands or chromosomes), an objective function is evaluated. The first initial generation was created. If the criteria for improvement are not met, the production of a new generation begins. Individuals are selected according to the value of their fitness to produce new individuals. New individuals are incorporated into the society to replace the parents, thus creating a new generation. This cycle continues until the criteria for improvement are met.

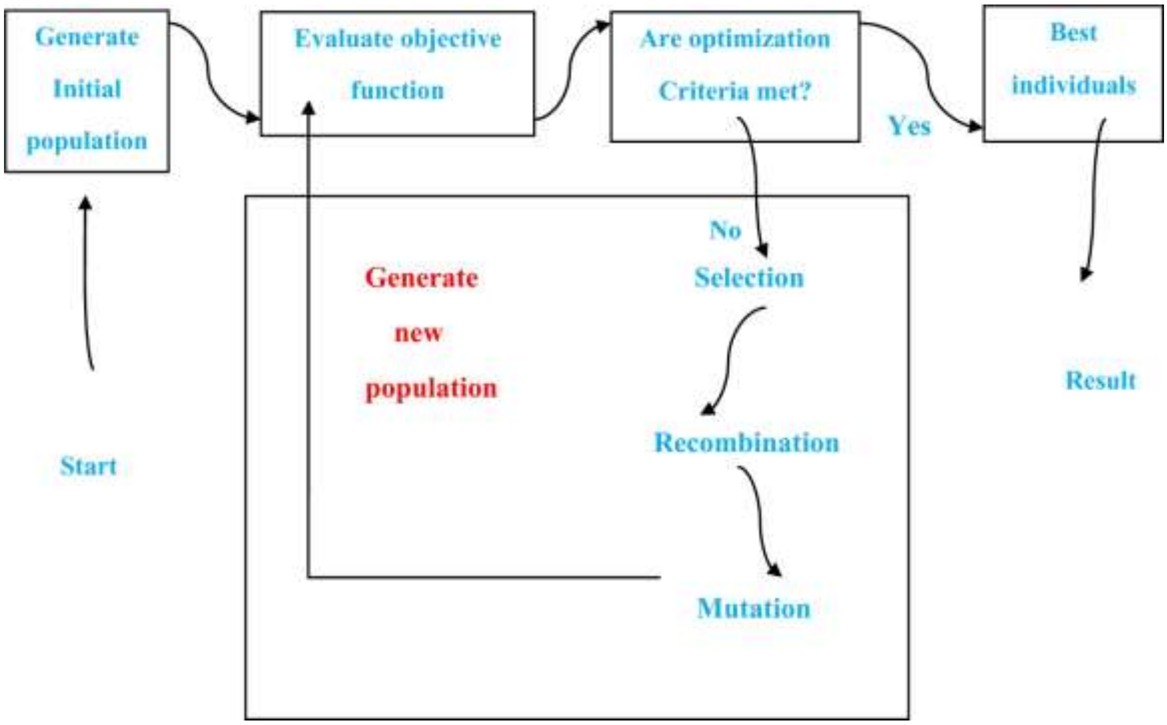


Figure (2) Structure of a Simple GAs

6. Case Study

The optimization problem was formulated according to AISC-LRFD provisions. Using a pipe, box, and angle sections are discussed for the single-layer barrel vault members which were selected from standard lists of AISC provisions. The procedure for solving this problem consists of two main levels: -

Level 1: Investigating the optimum braced barrel vault geometry using a genetic algorithm.

Level 2: Generating the geometry of braced barrel vault, calculation of external loads (dead and earthquake loads) analysis and fully stressed design of the braced barrel vault members, and calculating the weight of the braced barrel vault using the developed program.

Three cases were studied as follows: -

1- Pipe section single-layer barrel vault with span S = 30m, length L = 30m, depth to span ratio (H/S) = 0.05,0.1,0.15,0.2,0.25, and 0.3, number of divisions in span NS = 9, number of divisions in length NL = 9, 195 members, and 108 joints. The barrel vaults were subjected to combined dead and earthquake loads. The support condition was assumed to be fixed.

2- Box section single-layer barrel vault with span S = 30m, length L = 30m, depth to span ratio (H/S) = 0.05,0.1,0.15,0.2,0.25, and 0.3, number of divisions in span NS = 9, number of divisions in length NL = 9, 195 members, and 108 joints. The barrel vaults were subjected to combined dead and earthquake loads. The support condition was assumed to be fixed.

3- Angle section single-layer barrel vault with span S = 30m, length L = 30m, depth to span ratio (H/S) = 0.05,0.1,0.15,0.2,0.25, and 0.3, number of divisions in span NS = 9, number of divisions in length NL = 9, 195 members, and 108 joints. The barrel vaults were subjected to combined dead and earthquake loads. The support condition was assumed to be fixed.

Figure (3) shows the front & top view of the barrel vaults.

Table (1) presents the results of the case study (1) for pipe sections.

Table (2) presents the results of the case study (2) for box sections.

Table (3) presents the results of the case study (3) for angle sections.

Figure (4) shows the variation of weight according to depth to span ratio for the three cases study.

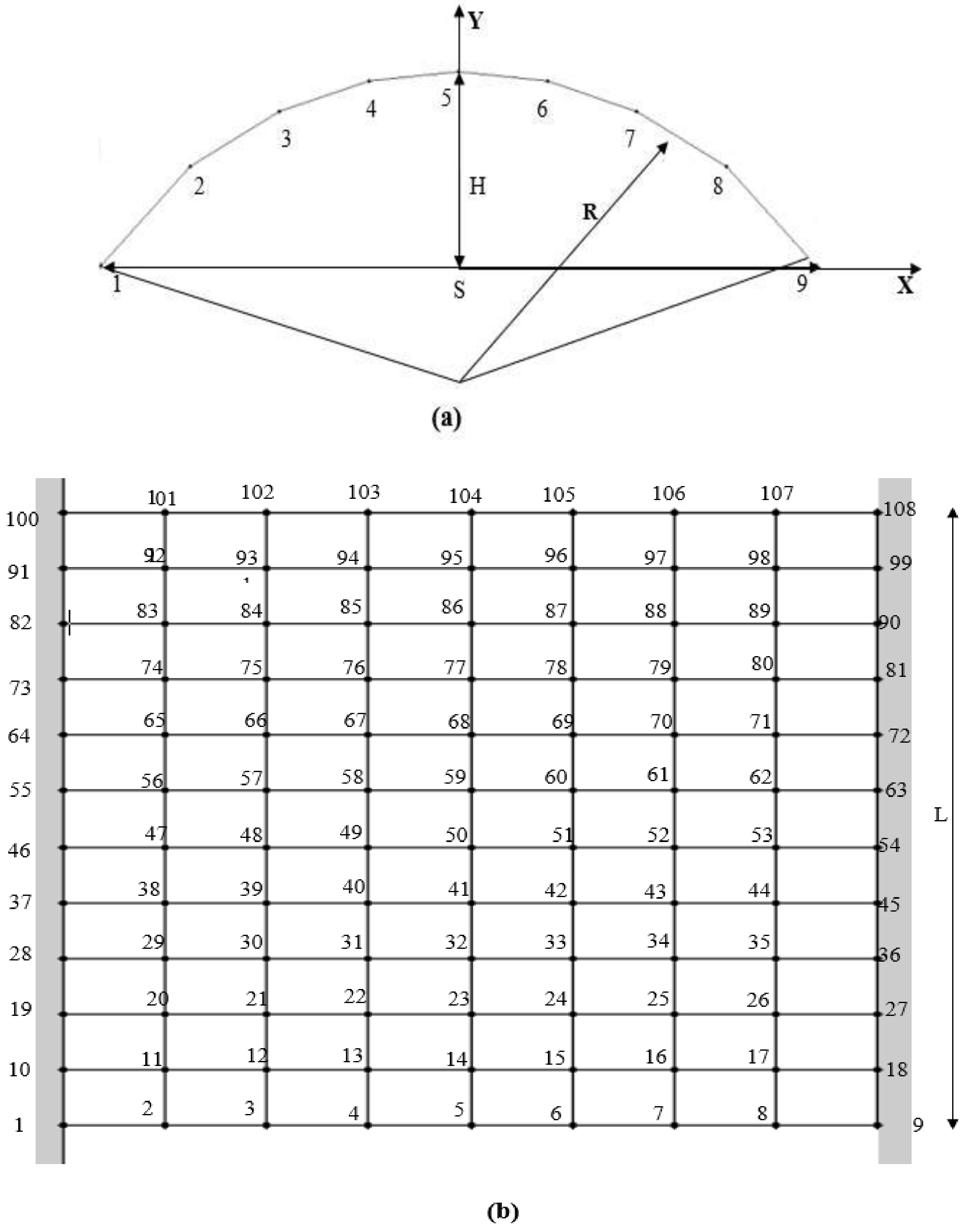


Figure (3) Steel Single Layer Barrel Vaults Geometry with S = 30m & L = 30m & 195 members (a)Front view (b)Top view

Table (1) Case study 1 results for pipe sections

(H/S)	Weight (KN)	Pipe section
0.05	69.3622	Pipe 12 Std.
		Pipe 8 Std.
		Pipe 5 Std.
		Pipe 10 Std.
		Pipe 2.5 Std.
		Pipe 1.5 Std.
		Pipe 1.25x-strong
		Pipe 2 Std.
		Pipe 2x-strong
		Pipe 1x-strong
0.1	51.9571	Pipe 10 Std.
		Pipe 6 Std.
		Pipe 5 Std.
		Pipe 8 Std.
		Pipe 2.5 Std.
		Pipe 1.5 Std.
		Pipe 1.25 Std.
		Pipe 2x-strong
		Pipe 1.25x-strong
		Pipe 1x-strong
0.15	42.5196	Pipe 3.5x-strong
		Pipe 3.5 Std.
		Pipe 2.5x-strong
		Pipe 4 Std.
		Pipe 1.5 Std.
		Pipe 1.25 Std.
		Pipe 0.75 Std.
		Pipe 1x-strong
		Pipe 1.25x-strong
		Pipe 2 Std.
		Pipe 1 Std.
		Pipe 0.75 Std.
0.2	29.9837	Pipe 3 Std.
		Pipe 2x-strong
		Pipe 2.5 Std
		Pipe 0.75x-strong
		Pipe 1 Std
		Pipe 0.75 Std
0.25	40.7277	Pipe 4 Std
		Pipe 2.5x-strong

		Pipe 3 Std
		Pipe 3.5 Std
		Pipe 1x-strong
		Pipe 1.5 Std
		Pipe 0.5x-strong
		Pipe 1.25 Std
		Pipe 1 Std
0.3	46.0479	Pipe 4 Std
		Pipe 3.5 Std
		Pipe 3 Std
		Pipe 2.5x-strong
		Pipe 3.5x-strong
		Pipe 1x-strong
		Pipe 0.75 Std
		Pipe 0.5x-strong
		Pipe 1 Std
		Pipe 1.25 Std
		Pipe 1.5 Std
		Pipe 0.75x-strong

Table (2) Case study 2 results for box sections

(H/S)	Weight (KN)	Box section
0.05	43.7416	HSS 3*3*3/8
		HSS 3*3*1/8
0.1	29.9722	HSS 3*3*5/16
		HSS 3*3*1/8
0.15	27.3505	HSS 2*2*3/16
		HSS 3*3*3/16
0.2	23.8682	HSS 2*2*3/16
		HSS 2*2*3/16
0.25	27.5143	HSS 2*2*3/16
		HSS 3*3*3/16
0.3	28.2763	HSS 3*3*5/16
		HSS 3*3*1/8

Table (3) Case study 3 results for angle sections

(H/S)	Weight (KN)	Angle section
0.05	46.3882	2L 3 x 3 x 5/16
		2L 3 x 2½ x 3/16
0.1	36.6445	2L 3 x 2½ x 5/16
		2L 3 x 2½ x 3/16
0.15	31.065	2L 2 x 2 x 5/16
		2L 2½ x 2 x 3/16
0.2	27.6404	2L 2 x 2 x 5/16
		2L 2 x 2 x 3/16
0.25	31.3585	2L 2 x 2 x 5/16
		2L 3 x 2½ x 3/16
0.3	33.2055	2L 2 x 2 x 5/16
		2L 2½ x 2 x 3/16

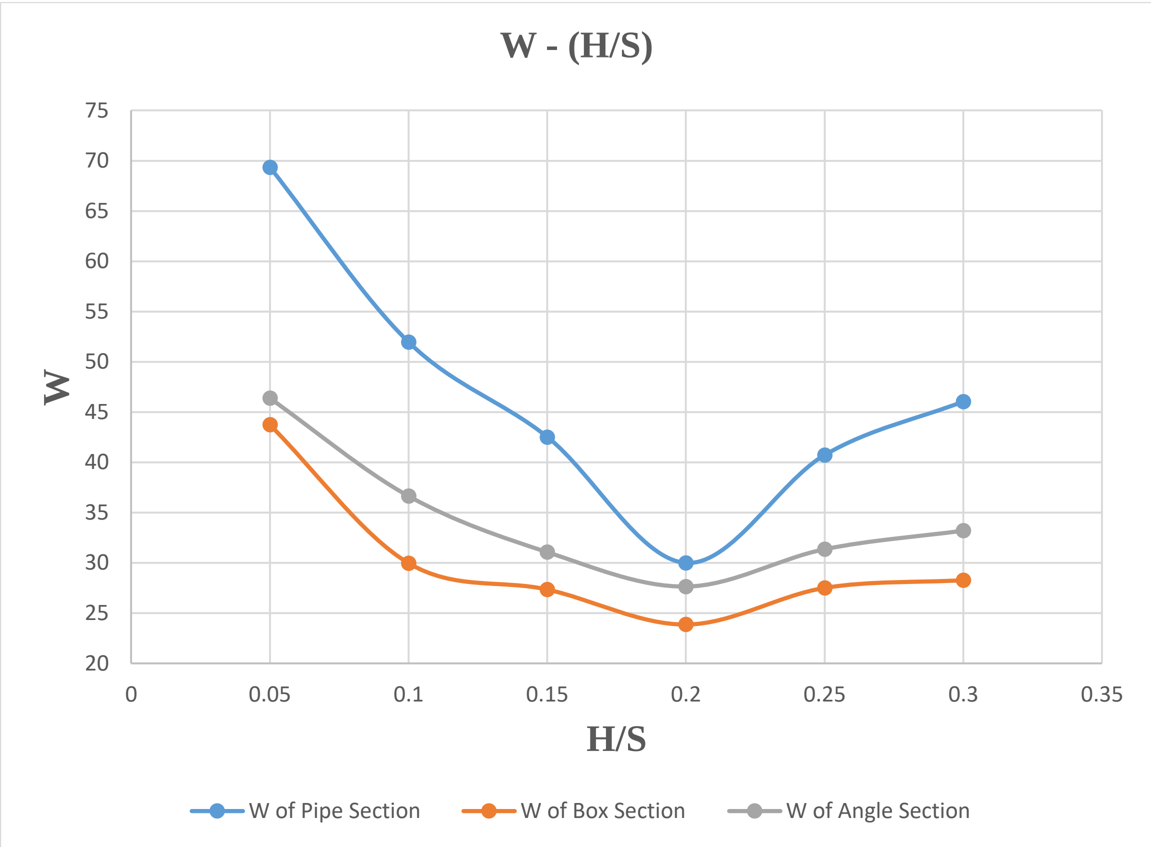


Figure (4) depth to span ratio – weight for the three cases study

7. Conclusions

Optimization of steel single-layer barrel vaults have been studied with span 30m and length 30m and depth to span ratio 0.05,0.1,0.15,0.2,0.25,0.3 and three types of sections which are pipe sections, box sections, and angle sections and the following conclusions can be observed:

1) The geometry parameters of the barrel vaults can efficiently treat as design variables, and considerable weight reduction can often be achieved as a result of geometric changes.
2) The weight of the barrel vaults increases with the increase of the depth to span ratio after 0.2.

3) The barrel vaults with a depth to span ratio of 0.2 has the greater reduction in weight for the three studied cases (pipe, box, and angle sections) so the ratio of 0.2 present the optimum case.

4) The barrel vaults with box sections have an optimum than the other section shapes (about 20.4% of that of the pipe section and 13.6% of that of the angle section).

5) Pipe section is not economic to use in this type of barrel vault.

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