Optimal Design of Overhead Tank Supporting Structure

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Abstract- The provision of water supply in most of the nations of the World is an obligation of the government but in some African countries especially Nigeria, the responsibility has shifted to the citizenry. Most of the structures used by some household to support their tanks to provide gravity flow of water have failed prematurely. In some cases, excessive materials have been used in the construction leading to high cost. This paper analyses and optimizes such supporting structures used by the most household. Patran/Nastran software was used for the analyses and optimization because of its efficiency. It was discovered that the final mass of water tanks (of capacity 2 cubic meters and 3 cubic meters) dropped from 1107.64Kg to 891.16Kg while that of 2 cubic meters and 5 cubic meters dropped from 1107.16Kg to 962.59Kg. The design is hereby recommended for domestic use as it will definitely reduce costs and eliminate waste of materials to the barest minimum.

Index Terms- optimal design, supporting structure, structural analysis

I. Introduction

The use of overhead tank support for load carrying purposes abounds in Africa, particularly in Nigeria's urban cities. Water is a commodity that everyone needs for various purposes ranging from drinking, washing, agricultural use, and so on. However, the provision of this life-threatening commodity is left on individuals to cater for in some countries like Nigeria. Even though The Nigerian Government has long agreed that the provision of water supply and sanitation services be the responsibility of the Federal, State and Local governments[1]. The United Nations as part of its Millennium Development Goals (MDGs) stipulates that by 2015 the population of people without sustainable access to safe water will be reduced by half. As a result of this, efforts were made by developed nations to increase the provision of domestic water and sanitation, but no serious efforts are made by the developing nations to meet this target[2]. Estimates of the investment in water supply and sanitation (WSS) required to meet 2015 sector MDG targets range from US$2.5 billion to US$4 billion annually[3] but today we are in 2017 the target is far from been achieved. So, every household that can afford to sink a borehole makes use of the overhead tank for water storage while others may patronize water vendor, like truck pushers. For the former, their tanks are supported with the structural arrangement made of steel pipes with a different cross section for carrying the water tank in a various household for domestic use as the ruling governments have failed to provide pipe born water for the citizenry. An example is shown in figure 1 below.

The purpose of this study is to analyze and optimize the structural arrangement used for the purpose of carrying overhead tank as some have failed prematurely while some use excessive materials in the construction leading to high cost

Structural analysis using finite element software has been in use for over three decades which has wider application in aerospace engineering for spacecraft structure and aircraft.

The finite element method (FEM) is a numerical method which can be used for the approximate solution of complex engineering problems. The method was first developed in 1956 for the analysis of aircraft structural problems. Thereafter, within several decades, the potentialities of the method for the solution of different types of applied science and engineering problems were recognized. Over the years, the finite element technique has been so well established that today it is considered to be one of the best methods for solving a wide variety of practical problems efficiently. One of the main reasons for the popularity of the method in different fields of engineering is that once a general computer program is established, it can be used for the solution of any problem simply by changing the input data[4].

With the use of finite element analysis software packages such as NASTRAN, ABAQUS, ANSYS, and others, it is possible to model structures in great detail and to examine their behavior under various static and dynamic load conditions. For instance, in a dynamic simulation, the structure's natural frequencies can be assessed and relative phase information of deflection shapes at different locations within the structure can be indicated. A number of thesis work has been handled by SUAT ONTAC, [5]and CIHAN [6] both works were on microsatellite structural analysis where vibration induced loads were investigated.

MACNEAL-SCHWENDLER CORPORATION (MSC) Patran/Nastran software had provided a user-friendly environment to accomplish structural design using Sol 200 where sensitivity analysis is automatically invoked when optimization is required.

Using sensitivity analysis Creto (1998) improve the frequency and mass of a Brazilian Scientific Satellite (SACI-1).[7], XIA[8] uses three methods, the modified feasible direction algorithm, sequential linear programming, and sequential quadratic programming to obtain an improved cross-sectional area of a large scale structural design.

In addition, Yin et al (1992) optimized a waffle panel which is a bidirectional stiffened panel to obtain an optimal design using sequential quadratic programming (SQP)[9].

In conjunction with structural analysis and optimization of MSC Nastran, automated systems have been used to solve complex and large-scale structural problems in the field of aerospace and engineering. Notable among them are (ASOS) automated structural optimization system[10], satellite optimization system SAT-OPT[11]. ASOS was used by Woo to reduce the weight of a honeycomb sandwich component of a scientific large-scale satellite using frequency constraints.

Through this work, optimal design, efficient load carrying capability and minimum cost of construction of the overhead tank supporting structure had evolved.

Figure 1 A household showing the overhead tank and its support in Satellite Town (Lugbe) Abuja Nigeria

ANALYSIS AND OPTIMIZATION

Static analysis and optimization which was done using (MSC) Nastran software were to verify the strength of the arrangement. A group of scholars has done a lot of work on analysis using Finite Element Method particularly using Nastran software though on different application but of the same principle as this study. Among them are found in these references[12][13][14][5][15], where various ways of using MSC Nastran in analyzing structures were established.

The application of structural optimization came to limelight as far back as 1960 when L. A. Schmit introduced the theory of mathematical programming into the structural design of cone shell which generally was accepted as a foundation for the research area[16]. Further presentations by the same author in providing different methods for effective structural synthesis have over the years had enhanced robust mathematical programming algorithms for efficient solution e.g. approximation concept in[17][18] and multilevel approach in [19][20] some uses genetic algorithm[21] and dual method[22].

II. METHODOLOGY

The analysis was carried out and then optimized. The process involved in design optimization consists of the following general steps [23]. The steps may vary slightly, depending on whether performing optimization interactively through the Graphical User Interface (GUI), in batch mode, or across multiple machines:

- ✓ Create an optimization design module which in this case was done in(MSC) Patran software,
- ✓ defining design variable (pipe cross-sectional radius) declaration
- ✓ defining the constraints, i.e. margin of safety ≥ 0
- ✓ design objective, that is to minimize mass and design study
- ✓ Initiate optimization analysis and wait for the process to run on MACNEAL-SCHWENDLER CORPORATION (MSC). Nastran
- ✓ Review the resulting design sets data and post-process results.

A general structural optimization (*SO*) problem can take the form as:

$$(SO)\begin{cases}\min f(x) \\ s.t. \quad g_j(x) \leq 0 \quad\quad j = 1 \dots . m\end{cases} \quad \dots\dots\dots.. (1)$$

Where f(x) is the objective function,

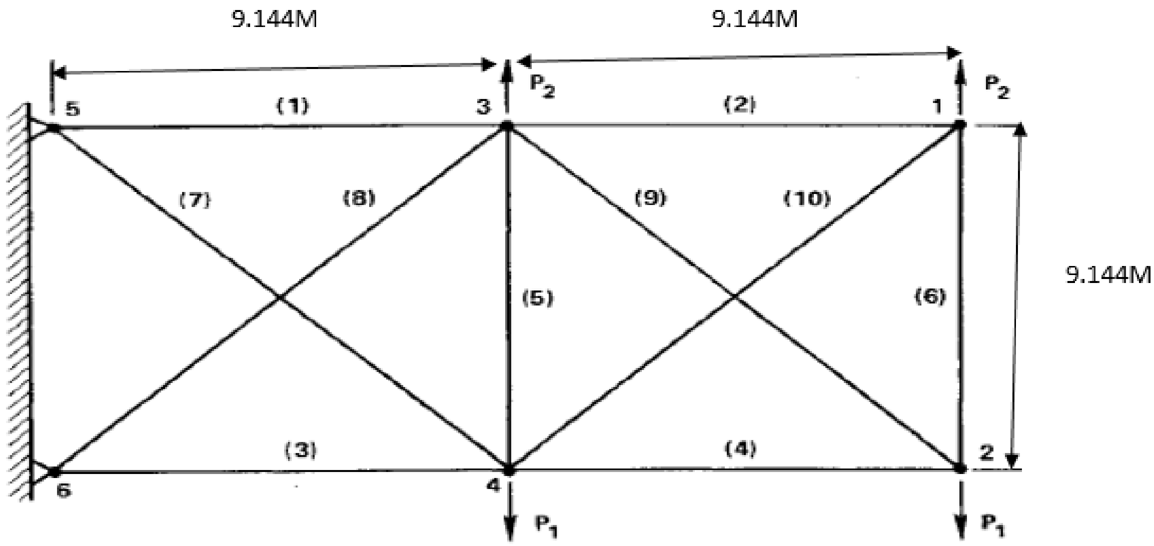
$x = \{x_1, x_2, \dots\dots x_n\}^T$ and $g_j(x) \leq 0 \quad j = 1 \dots . m$ are design and constraints variables respectively.

The optimization problem statement requires an explicit description of the design objective, as well as bounds which define the region in which it may search[16].

Before the optimization report is presented as a numerical example to test the efficiency of the software was examined.

III. TEST EXAMPLE

The example problem presented is a familiar ten member planar truss (see Fig. 2) for which results have been previously reported in[24]. The material properties, stress limits, minimum member sizes, and load condition data for this example are given in Fig. 2 and results are given for four distinct cases in Table 1 and 2. Cases 1a and 2a involve stress and minimum member size limits only while Cases 1b and 2b include vertical displacements limits of ±2.0 in at all points in addition to the stress and minimum member size constraints. No design variable linking has been employed in this example. The minimum weights obtained are essentially the same as can be seen in the following two tables 1 and 2.



MATERIAL: ALUMINUM, E = 10^7 psi,   = 0.1 pci

STRESS LIMITS: ±25000psi (ALL MENBERS)

LOWER LIMITS: 0.00254 M (ALL MEMBERS)

UPPER LIMITS: NONE

LOADING CASE 1: SINGLE LOAD P_1 =100K, P_2 = 0

LOADING CASE 2: SINGLE LOAD P_1 150K, P_2 = 50K

Figure 2 Ten bar truss

Table 1 Previous result as reported in[24] [15]

Case	Minimum weight (kg)	No of analysis	CPU run time (sec)	Member areas for optimum design (m^2), all values in multiple of 10^{-3}									
				1	2	3	4	5	6	7	8	9	10
1a	722.66	20	0.9	5.12	0.06	5.21	2.54	0.06	0.06	3.71	3.59	3.59	0.06
1b	2308.33	23	1.0	19.61	0.06	15.36	9.54	0.06	0.06	5.39	13.38	12.70	0.06
2a	755.00	20	0.9	3.84	0.06	6.49	2.55	0.08	1.32	5.52	1.78	3.60	0.06
2b	2128.16	22	1.0	15.14	0.06	16.35	9.23	0.06	1.27	8.17	8.09	14.17	0.06

Table 2 Present work result for ten bar truss

Case	Minimum weight (kg)	No of analysis	Member areas for optimum design (m^2), all values in multiple of 10^{-3}									
			1	2	3	4	5	6	7	8	9	10
1a	723.48	17	5.12	0.06	5.21	2.54	0.06	0.06	3.71	3.59	3.59	0.08
1b	2296.09	15	19.61	0.06	15.36	9.54	0.06	0.06	5.50	13.52	13.45	0.06

2a	755.23	15	3.84	0.06	6.49	2.55	0.07	1.32	5.52	1.78	3.60	0.06
2b	2115.55	12	15.14	0.06	16.35	9.23	0.06	1.27	7.98	8.27	13.01	0.06

As shown in table 1 and 2, the present study is in agreement with previous work so, the application of (MSC) Nastran is reliable for the current optimization procedure.

IV. THE FINITE ELEMENT MODEL OF OVERHEAD SUPPORTING STRUCTURE

The mathematical model which is the translation of the physical system was obtained using MACNEAL-SCHWENDLER CORPORATION (MSC). Nastran/Patran software which ensures that the model was as close as possible to the actual system by using appropriate interpolation function. The steel pipes were modeled using beam element while shell elements were used for the sheets of metal used to transfer the load to the steel pipes to enhance uniform pressure on the supporting steel pipes. Figure (3) present the FE model of the structure.

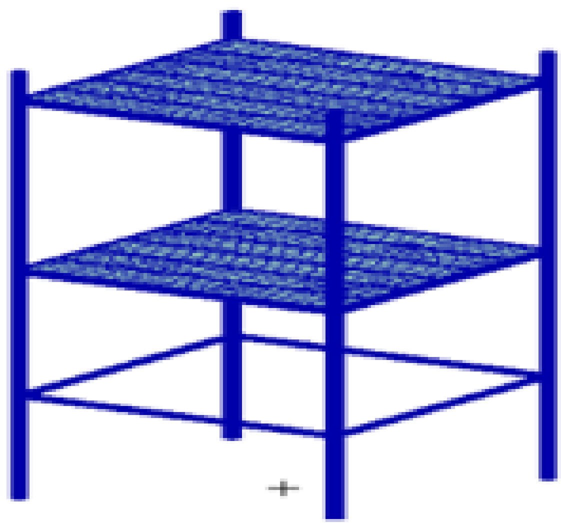


Figure 3 FE model of the overhead support structure

The arrangement was made of 4 vertical steel pipes of 5m in length each, 9 horizontal arrangements of steel pipes in a different orientation of 2m in length each and of two sets that interface the two tanks. Another 4 horizontal steel pipes were used to brace the lower part to increase the stability of the arrangement. The entire arrangement is as shown in figure (3) above.

Material: the steel pipes were made of steel of mechanical properties 210GPa elastic modulus, 241MPa as allowable yield strength [25]

Load: two tanks were used, 2000litres tank on the top, and 3000litres on the second set. These were converted to pressure as follows:

$$\text{Mass} = \text{density of water} * \text{volume} = \frac{1000\text{kg}}{\text{m}^3} * 2\text{ m}^3 (\text{i.e. } 2000\text{litres} =$$

$$Force = mass * acceleration\ due\ to\ gravity = 2056kg * 9.81m/s^2$$

Cross sectional area, A was calculated as $2.07m^2$(1.625m diameter of tank)

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{2056 * 9.81}{2.07} = 9743.65\text{Pa for 2000liters and 14}$$

V. RESULT AND DISCUSSION

The stress distribution after optimization is shown in figure (4)

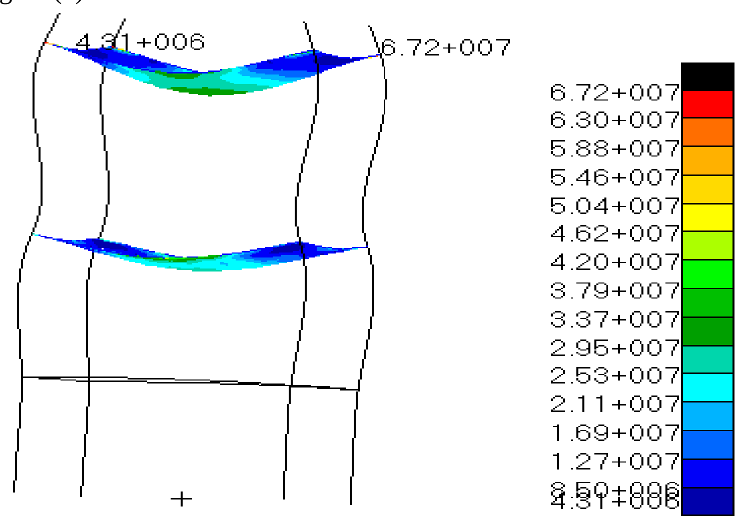


Figure 4 Stress distribution

The maximum stress as shown above figure 4 is 67.2MPa which is lower than the allowable yield strength.

Load case: two load cases were used, case 1: 2 cubic meters and 3 cubic meters (2 M^3 and 3 M^3), and case 2: 2 cubic meters and 5 cubic meters (2 M^3 and 5 M^3), the result are shown in the following table 4.

Table 3 OPTIMIZATION RESULT IN METERS

		All values are in meters			Optimal Design	
S/No	Label	Initial (X 10^{-3})	Lower (X 10^{-3})	Upper (X 10^{-3})	Case 1 2 M^3 and $3M^3$ (X 10^{-3})	Case 2 2 $M^3$and 5 M^3 (X 10^{-3})

1	A1	38	10	80	18.982	43.864
2	A2	34	10	40	13.149	39.416
3	B1	38	10	80	14.712	14.267
4	B2	34	10	40	10	10
5	C1	40	10	80	24.589	27.564
6	C2	34	10	40	18.589	22.52
7	D1	30	10	80	11.465	11.366
8	D2	28	10	40	10	10

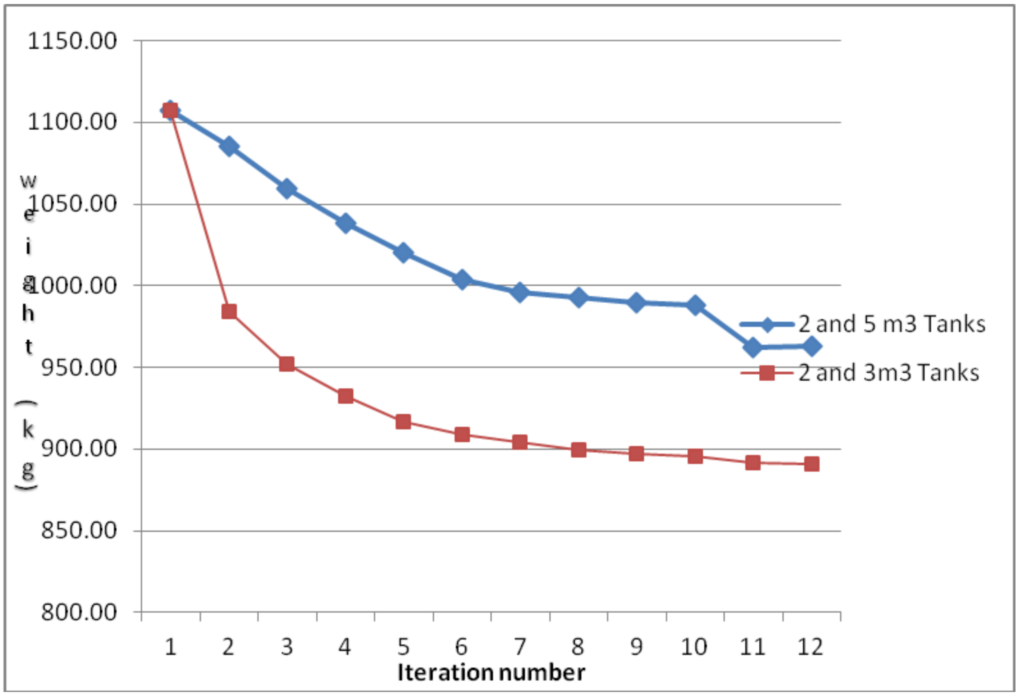


Figure 5 OBJECTIVE ITERATION CYCLE

A1,2 refer to the outer and inner radius of upper horizontal steel pipes respectively, B1,2, are for outer and inner radius of middle horizontal steel pipes, C1,2 gives the outer and inner radius of vertical steel pipes and D1,2 refer to the lower four horizontal steel pipes for stability. It's important to note that this design is only for these load carrying capability as other loads different from these must be analyzed and optimized to avoid premature failure or excessive use of materials.

VI. CONCLUSION AND RECOMMENDATION

1. Through the example presented the validity of the design can be ascertained and the software trusted.
2. The final mass of 2 cubic meters and 3 cubic meters volumes of water tanks arrangement has dropped from **1107.64Kg** to **891.16Kg** while 2 cubic meters and 5 cubic meters drop from **1107.16** to **962.59Kg** as shown in figure (5) which satisfied the weight reduction objective.
3. As table 3 depicts, A1 has a maximum radius of 44mm, A2 radius of 39mm, B1,2 and C1,2 are as shown, which are readily available in the market.
4. The design is hereby recommended for domestic use as the aim of this study is to ease difficulties in terms of cost and material resources

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