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OPTIMIZATION OF HEAVY SLAB FORMWORK SYSTEMS USING SHORING TOWERS

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ملخص البحث:

يعتبر تصميم الشدات مرحلة هامة و مؤثرة في تكلفة العناصر الانشائية الخرسانية المسلحة عند تنفيذ اي مشروع. و لذلك فمن المهم البحث عن الشدة التي تحقق الامان الكافي من الناحية الانشائية بالاضافة الي انها يجب ان تكون اقتصادية و ذلك لن يحدث الا عن طريق عمل التصميم الامثل الذي يجمع بين اقل وزن مع اقل تكلفة للشدة. و مع ظهور الشدات الحديثة و كثرة انواعها طبقا للشركات المصنعة لها لذلك يجب استخدام هذه الانواع من الشدات. تتكون هذه الشدات من تطبيق البلاي وود, كمرات ثانوية, اخري رئيسية (خشبيه او حديد) و الابراج السائدة ذات الطبقات المتعددة(Shoring Towers) كعناصر تحميل رأسية و التي تكون في اغلب الاحوال هي الحل الامثل في حالة البلاطات الثقيلة و الارتفاعات العالية مثال علي ذلك بلاطات الكباري. تم عمل برنامج علي MATLAB يسمي ب FWSS يحتوي علي مجموعة من الشاشات للمدخلات و اخري للمخرجات و هي سهلة الاستخدام لمهندس التشييد. وتشمل شاشة المدخلات معلومات عن المشروع مثل اسم المشروع, مكان المشروع, نوع المشروع, اسم المستخدم و ايضا تشمل معلومات عن البلاطات الخرسانية نفسها مثل سمك البلاطة, ارتفاعها, ظروف التحميل و وزن الخرسانة المستخدمة. ايضا يشمل هذا البرنامج شاشة للمخرجات مثل جميع العناصر المختاره للتصميم (نوع التطبيق, نوع الكمرات الثانوية و الرئيسية) و المسافات بينهم. هذا كله عن طريق الاعتماد علي دالة الهدف التي وضعت لتحقيق اقل وزن للشدة و الاخري التي وضعت لتحقيق اقل تكلفة للشدة مع الاخذ في الاعتبار شروط الامان و يتم الحل بحيث تستوفي كل القيود المطلوبة مثل قيود التصميم, التحميل و الارتفاع المطلوب. لحل دالة الهدف هذه تم استخدام الخوارزميات الجينية للحصول علي الحل الامثل لما تتميز به من قوة في حل هذا النوع من الدوال و بذلك يتحقق التصميم الامثل للشدة.

Abstract

Design of formwork has become more important and effective in overall cost of construction projects. The construction of heavy and high concrete slabs is considered as a complicated problem in projects because they need very efficient and economical formwork systems to carry vertical loads. So, designers focused on Shoring towers because it is the optimal solution for this problem as they are modular, can be used a large number of time, much faster to erect and have high loading capacity. Thus, the need to study this type of formwork is extremely needed due to increase in demand on them. Therefore, this paper introduces a computer model (FORMWORK SELECTION SYSTEMS) called FWSS was built on MATLAB for civil engineers based on genetic algorithms as an optimization technique to selects the optimal solution on determining the minimum weight and minimum cost of slab formwork from the database which stored in the model. An example is provided to discuss and proof results of this computer model.

KEYWORDS: Formwork Design, Cost, Optimization, Shoring tower.

1. Introduction

A formwork is a structure used to contain poured concrete until it molds to the required dimensions. Different formwork systems provide a wide range of concrete construction solutions that can be chosen to suit the needs of a particular structure. Formwork development has paralleled the growth of concrete construction throughout the 20th century. (Hurd, M. K. (1989). Formwork systems in buildings may be broadly classified into horizontal and vertical formwork. Horizontal formwork system is used to support the horizontal concrete elements as (slabs and roofs). Vertical formwork system is used to support the vertical concrete elements as (wall and columns). Formwork for heavy and high-clearance concrete construction is commonly based on shoring towers, which is termed to load towers or support towers. Shoring towers are frame base systems, built from tube and coupler systems. Shoring towers of various heights are an inseparable part of the construction scene in commercial, residential, industrial, public, and civil engineering projects all over. So, different shoring tower types may set different projects and different needs of the contractor. Therefore, shoring towers appears as the common solution for construction of heavy slab formwork. The market has responded to the demand for shoring towers by offering numerous proprietary models, from which the contractor can choose from it. Figure (1) shows an example for the types of towers.

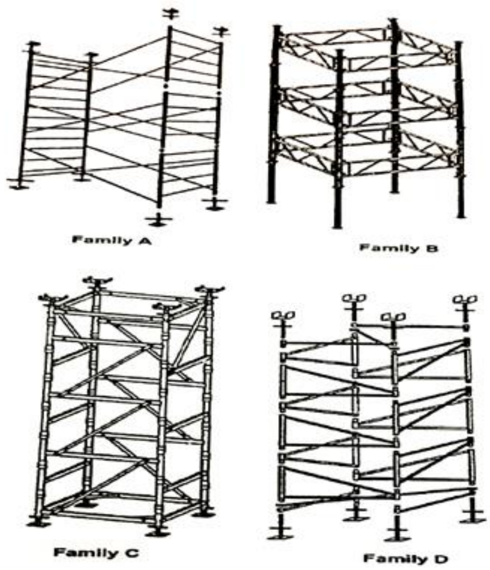

Figure (1): Example of tower configurations. (Shapira & Raz, 2005)

Therefore, it is necessary that contractors familiarize themselves with the variety of tower systems offered on the market, as well as the criteria by which to judge suitability of various tower types to their needs (Shapira and Raz; 2005). Although shoring towers are sometimes used for other purposes than concrete formwork such as temporary support scaffolds for precast concrete elements or as access scaffolds for workers, tools, and materials. This paper studied shoring towers only as formwork.
Shoring tower systems are different from each other in their basic frame configuration. They are made of either steel or aluminum, or a combination of both. It may also be characterized according to different load bearing capacities, variety of horizontal and vertical frame dimensions, weight of frames and other members.

An ideal tower doesn’t exist, as there would always be some trade off in terms of simplicity of assembly, weight of components, tower versatility, and numbers of small loose parts. Shoring towers are currently available and commonly used in construction field, as they had addressed with carrying capacities of 45–80 KN per leg (Shapira & Raz, 2005). Towers in this class, i.e., heavy duty towers, are those used extensively in building construction, and to some extent also in civil engineering projects (e.g., highway and bridge construction). The next class, of extra-heavy-duty towers, includes towers with carrying capacities of up to 200 KN per leg, mostly used for heavy civil projects. One may justifiably argue that the 100–130 KN per-leg range should belong in the heavy-duty class. It should be borne in mind, though, that with the typical building construction loads on the one hand, and the size of the elements commonly used as stringers and joists which limit tower spacing (Shapira & Goldfinger, 2000) on the other hand, a 120 KN per-leg tower is likely to be extremely underutilized in most cases of “regular” building construction.

The construction of formwork cost accounts for 40 to 60 percent of the cost of the concrete frame and for approximately 10 percent of the total building cost (Hanna 2005). Thus, selecting an appropriate formwork system plays an important yet challenging role in achieving significant cost savings and primarily uses the subjective decisions of site engineers. Therefore, a rational approach is needed to assist contractors in selecting the optimal form system considering the most governing factors in the decision-making process. Many attempts have been made to find a satisfactory solution for the optimal concrete formwork system for the horizontal or the vertical systems. A number of studies are discussed on an approach called Rational Design, which is mean design based on a structured procedure that yields solutions that both meet the static requirements and are economical. These studies whether general [e.g., (Peurifoy R. L., 1976), and (Hurd, 1989)] or specific [e.g., (Ringwald, 1985)].

Typically addresses conventional formwork design with a rational approach for common concrete elements (e.g., regular-height slabs, beams, and walls). [(Christian, 1987), and (Tah & Price, 1991)] focused on computerized solution, they have taken the issue even further and developed. However, one type of conventional formwork-although widely used-has received little attention with regard to rational design, this type is formwork for elevated (i.e., heavy and higher than normal) elements having steel or aluminum shoring towers as the form’s main vertical support. (Hurd; 1995), (Peurifoy & Oberlender; 1996), and (Hanna; 1999) pay only limited attention to shoring towers, usually within the general presentation of vertical shoring solutions, and chapters in books, dealing exclusively with towers, are few (Bennett & D’Alessio; 1996). Technical manufacturer catalogues traditionally provide useful information on specific products. Various economic aspects of formwork design and practice with shoring towers have been treated during recent years, with special focus on high multitier towers (Shapira; 1995), (Shapira & Goldfinger; 2000), and (Shapira, Shahar, Raz; 2001), (Shapira; 2004). Those studies on high towers were motivated mainly by the high cost of tower-based formwork relative to the overall construction cost of the supported concrete element. Also, (Shawki KM, Emam MA, EL-B Osman 2012) wrote about the characteristics of shoring towers that they are made up of hand carried elements and are assembled a new for each use; they may be regarded as traditional formwork. Their industrialized natures are distinct. All previous studies are concentrated only on giving correct and organized approach and may some of them computerized they approaches as [(Shawki KM, Emam MA, EL-B Osman 2012) and (Slawomir Biruk, Piotr Jaskowski; 2016)].

So, all these attempts was helpful and definite introduce methods to help in reducing time and cost. This paper will introduce a method not only structured or computerized but also with optimization in formwork weight based on genetic algorithms as an optimization tool to get the optimal solution with minimum weight or minimum direct cost.

2. Genetic Algorithms

Genetic algorithms (GAs) are a technique that this paper depends on it to get the optimum solution. Genetic algorithms (GAs) based on the principles of natural selection and evolution; also they are applied to solve the optimization problem. Genetic algorithms search from a population of possible solutions limited by a set of constraints. In this paper, the cost and weight of formwork components were considered for the formulation of the objective function. Computer model (FORMWORK SELECTION SYSTEMS) called FWSS built on MATLAB discuss formwork design problem by providing optimum design parameters such as optimum spacing between form members, optimum weight and cost for formwork unit.

The Genetic Algorithms (GAs) was first introduced by John Holland in the 1960s; then the technique was developed in the University of Michigan during 1960s and 1970s by Holland and his students. In the beginning, Holland's studies were not oriented to design an evolutionary algorithm for solving specific problems, but he was just studying the natural adaptation phenomenon and he was trying to find a method to simulate its mechanism. Holland published in 1975 the first book that presents the genetic algorithms; it was titled “Adaptation in Natural and Artificial Systems”. This book gave a full presentation of the theoretical framework of natural adaptation under the GA, and the method of simulation of the biological evolution (Holland J., 1975). Genetic algorithms have been demonstrated to be robust heuristic search techniques that are capable of rapid identification of optimal design options whilst avoiding convergence on local optima.

Many scientists worked in the field of GA development and its application such as, David Goldberg 1989 ... etc. They developed most of the currently known types of GA, but they all still give Holland the nickname "The father of GAs".

3. Basic Tower Layout

A basic tower layout (Figure 2) is composed of a uniform tower grid, in which the distance between the towers in each of their two directions are the same (but the distance in one direction is not necessarily identical to those in the other) (Shapira 2005). One direction of the tower grid is also the direction of the Joists; the other is the direction of the stingers.

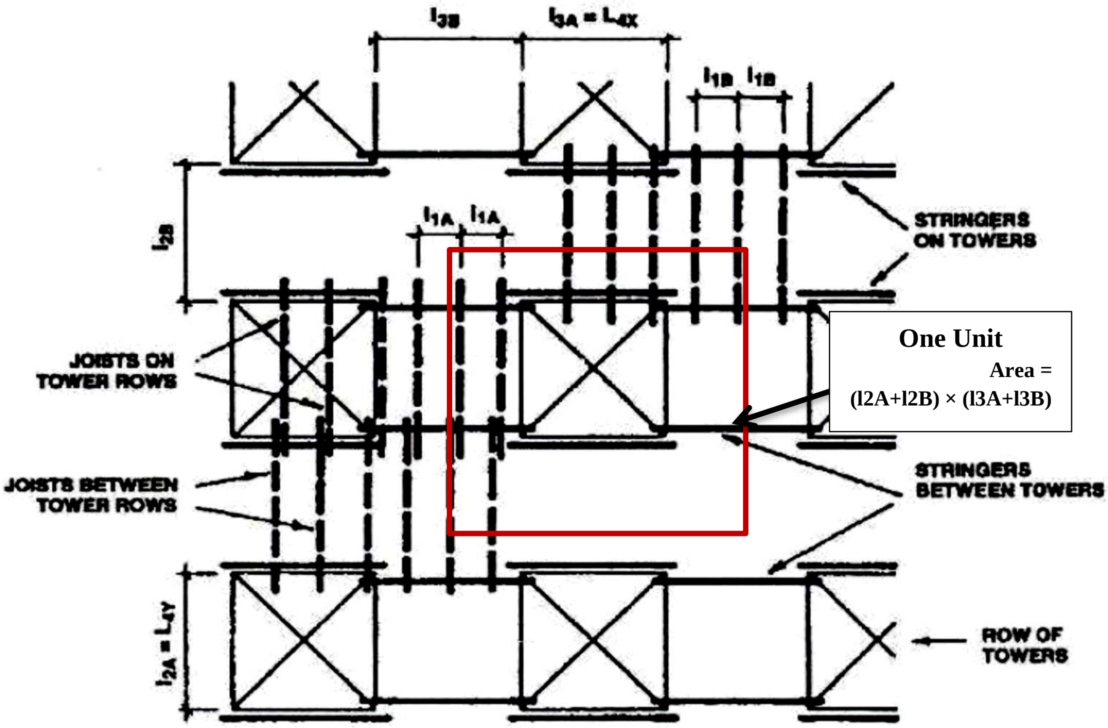

Figure (2): Basic Tower Layout + Area carried by one tower (Shapira, 1995)

We arbitrarily define the direction of the stringers as the direction of "tower rows." Thus we refer to distances between rows, and to distances within rows. The row direction (also the stringers') is designated X, and the perpendicular direction (also the joists') is designated Y.

A distinction is made between elements lying "on towers" or "on tower rows," and those lying "between towers" or "between tower rows." Stringers lying on towers and joists lying on tower rows are assigned the subscript A, and stringers lying between towers and joists lying between tower rows are marked by the subscript B (Shapira, 1995).

Formwork elements are assigned identifying subscripts as follows:

1- Sheathing; 2- joists; 3- Stringers; 4- Towers.

A distinction is made between an element's fixed length, L, and its calculated and determined span, l, in a given tower layout. Note that the span of element I is, by definition, the distance between elements i + 1 (i = 1, 2, 3). The variables L and l assume somewhat different roles in the case of towers (i = 4): l is not applicable, and L4X and L4Y are the tower's respective horizontal dimensions in the direction of the stringers and joists. By these definitions, we also get l2A = L4Y, and l3A = L4X.

4. Objective function

The objective function for this problem can be written as follows:

Weight of one unit (Wmin.) =

$$[(L2A + L2B) \times (L3A + L3B) \times Wp] + [(L2A + L2B) \times Ns.b. \times Ws.b.] + [(L3A + L3B) \times Nm.b. \times Wm.b.] + \left[(W\,U.T + W\,L.T + \textstyle\sum_{n=1}^{i} W\,M.T\right] \tag{1}$$

Unit Cost of one unit in (L.E) =

$$\Big[\big((L2A + L2B) \times (L3A + L3B) \times unit\ cost\ of\ plywood\big) + [(L2A + L2B) \times Ns.b. \times Unit\ Cost\ of\ s.b.] + [(L3A + L3B) \times Nm.b. \times Unit\ Cost\ of\ m.b.] + \big[Unit\ cost\ of\ U.T + Unit\ Cost\ of\ L.T + (\textstyle\sum_{n=1}^{i} Unit\ cost\ of\ M.T)\big]\Big] \tag{2}$$

Where:

W min.: Minimum overall weight of one unit of tower (kg).
l2A: Maximum joist span on towers rows (m).
l2B: Maximum joist span between towers rows (m).
l3A: Maximum stringer span on towers rows (m).
l3B: Maximum stringer span between towers rows (m).
W_P: Weight of plywood (kg/m2).
Ns.b. : Number of joist elements per one unit.
Ws.b. : Weight of joist (kg/m).
Nm.b.: Number of stringer elements per one unit.
Wm.b.: Weight of stringer (kg/m).
WU.T: Weight of upper tier of shoring tower (kg).
WL.T: Weight of lower tier of shoring tower (kg).
WM.T: Approximate weight of middle shoring tower (kg).
n: Number of middle towers.

4.1 Constraints

Three types of constraints are imposed on the generated solutions to ensure the development of practical formwork elements:

1- Design constraints:

A) The vertical load calculated due to slab condition must be bigger than the minimum value for vertical loads according to ACI 347R-94 for normal conditions equal 4.8 KPa, when motorized carts are used equal 6.0 KPa if this condition not achieved takes the minimum value for vertical loads as the design vertical load.

V.L > V.L min (3)

B) The span of the joists lying between the tower rows (the spacing of the tower rows) (l2Bmax) must be bigger than L2, where L2 = length of the joist, if this condition not achieved then recalculate using bigger section of joist.

l2Bmax > L2 (4)

C) The span of the joists lying between the tower rows (the spacing of the tower rows) (l2Bmax) must be bigger than L4Y, where L4Y = the length of the tower in parallel to the direction of the joist, if this condition not achieved then substitute n1= n1 + 1 and repeat until l2Bmax is obtained that meets the condition.

l2Bmax > L4Y (5)

D) The span of the stringers lying between the towers (the tower spacing within the rows). (l3Bmax) must be bigger than L3, where L3 = length of the stringer, if this condition not achieved then recalculate using bigger section of stringer.

$$l3Bmax > L3 \qquad (6)$$

E) The safe carrying load capacity of each tower leg (PT) must be bigger the calculated load carrying capacity per one leg, if this condition not achieved then these solution unsafe try another one.

$$PT > V.L \times [(l2B + L4y)/2] \times [(l3B + L4X)/2] \qquad (7)$$

2- <u>Bearing constraints:</u>

The bearing stresses between joists and stringers must be smaller than allowable bearing stress according to type of material for these members. Also, bearing stresses between stringers and the u-head of the shoring towers must be smaller than allowable bearing stress according to type of material for these members.

3- <u>Stability constraints:</u>

A) The cross section of the stringers (main beams) must be bigger than the cross section of the joists (secondary beams) for the same material.

B) The remain height from the ceiling height after subtracting the height of sheathing, joist and stringer elements and also after calculating the number of tiers must not exceed 60 cm (where the 60 cm are the recommended extension for both upper and lower jack spacers).

5. COMPUTER MODEL FWSS

A computer model (FWSS) was built on MATLAB by using G.U.I toolbox to make it easier for the user. The objective function of this model is to minimize the weight and cost of the overall formwork system. Six steps are required to run FWSS model as follows:

<u>Step 1:</u> Write FWSS.m on command window to run FWSS.

<u>Step 2:</u> This edit box as shown on Figure (3) is the main model screen which Contains two parts, the first on the left includes project information such as project name, type, location and user's name, while the second part on the right includes project data such as slab thickness (t_s), slab height, concrete unit weight, loading conditions and live loads. The user presses SAVE to save the entry data.

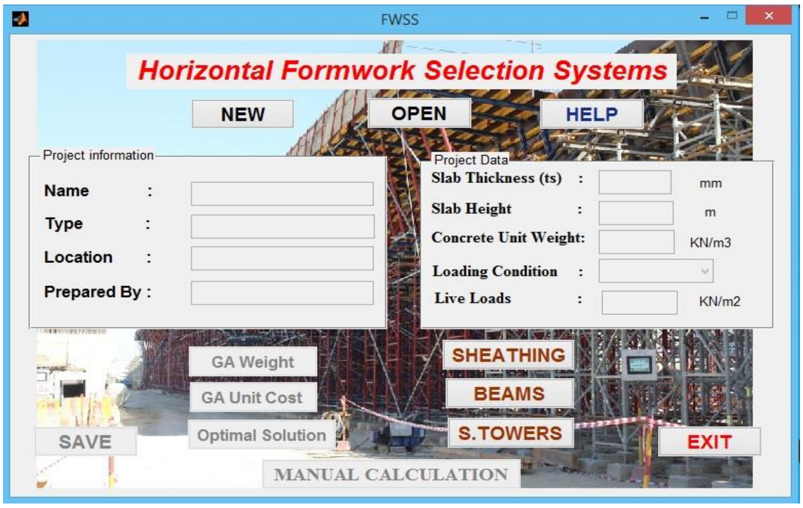

Figure (3) Main Program screen

Step 3: Figure (4) includes information about plywood sheathing such as thickness, dimensions, weight, unit cost in LE/m^2, stiffness capacity EI, section capacity in bending and rolling shear. Also, when BEAMS button is pressed as shown in Figure (5) the user defines the dimensions, section properties, weight and unit cost in LE/m for secondary and main beams. So, the user can choose type of beams either timber or steel. Then ADD, SAVE, or DELETE to go to edit box as shown in Figure (3).

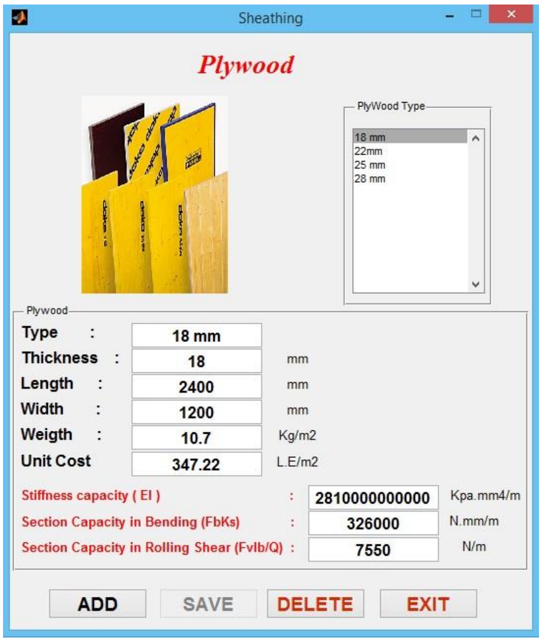

Figure (4) Plywood Sheathing screen

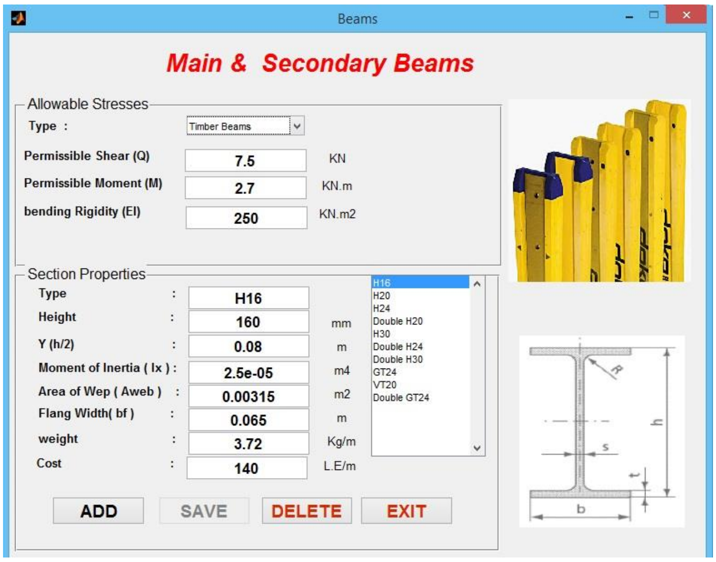

Figure (5): Beams screen (main and secondary beams)

Step 4: The user press S.TOWERS button to go to edit box as shown in Figure (6). The edit box contains all information about the shoring towers .The user can use the types stored in model data base or ADD, DELETE other shoring towers types, press SAVE will return to edit box shown in Figure (3).

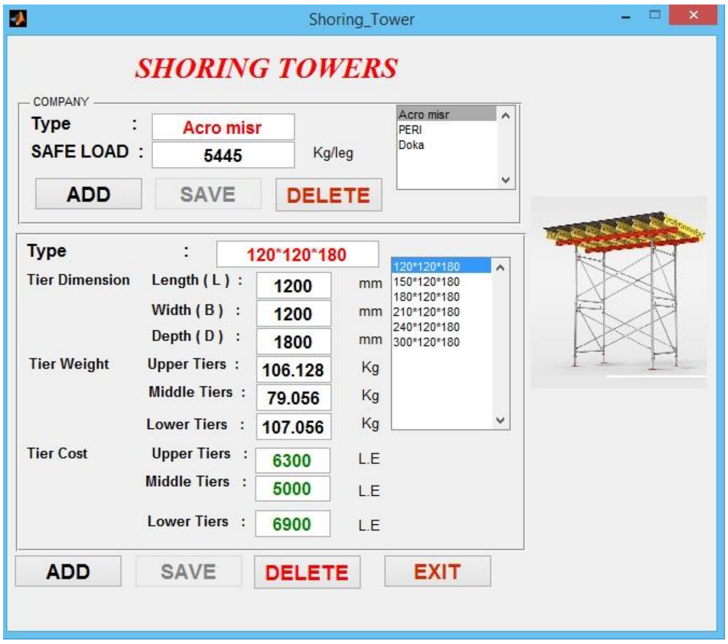

Figure (6): The shoring towers screen.

Step 5: FWSS MODEL can perform many options of calculations for formwork weight or cost, when MANUAL CALCULATION button is pressed as shown in Figure (3), the output of this step is shown in Figure (7), in this case model can check the structure safety for all members of formwork only.

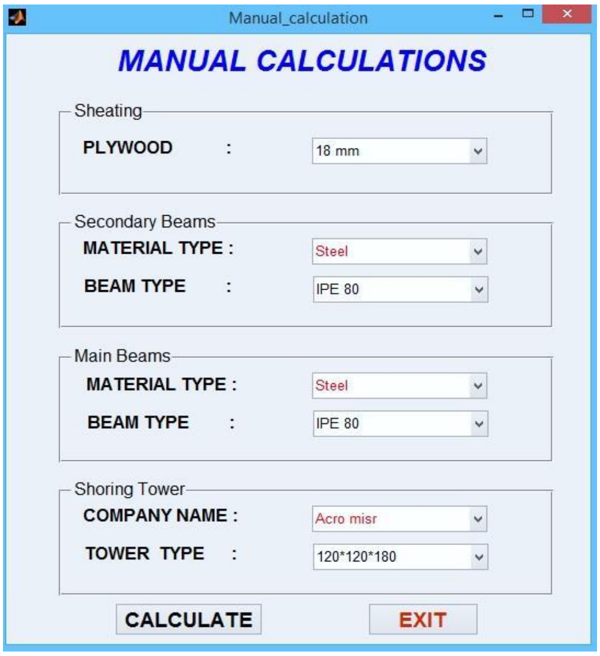

Figure (7): Manual calculation screen.

Step 6: If user want the optimum solution, GA weight and GA Unit cost buttons are two available options as the model will search for the optimum solution based on determining minimum weight in case of (GA weight) or minimum cost in case of (GA Unit cost) by using formwork components that stored in the data base before by the user. Also, Optimal Solution button is a simple optimization technique which gets optimal design solution by combination between minimizing weight and cost of formwork.

6. EXAMPLE

This example discuss and proof the result which determine the optimum design by calculating minimum weight and cost for slab of deck bridge of thickness t_s=350 mm and slab height 8m. Loading condition will be normal condition and live load equals 2.4 KN/m^2. In this example, the formwork components consists of plywood sheathing 25mm, timber beams H20 for secondary beams, double UPE 120 rolled steel sections for main beams and shoring towers (Acro misr 210×120×180) as a vertical members.

The inputs and outputs of the model are as shown in Figures (8) and (9). Figure (8) contains project information's and project data such as slab thickness, slab height, concrete unit weight, loading conditions, live load, and type of material for secondary and main beams.

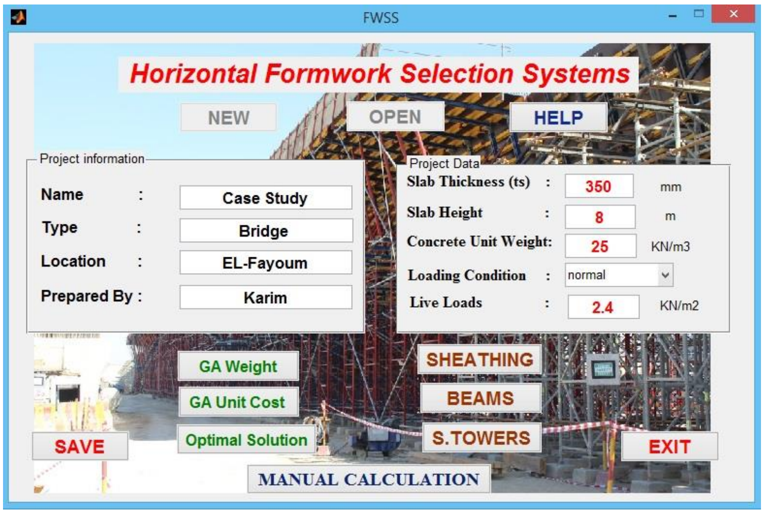

Figure (8): The project information's.

Figure (9), (10), (11) and (12) contains all formwork output items such as plywood thickness, type of secondary, main beams and type of shoring tower. Also, the output contains secondary, main beams spacing, number of middle towers.
If MANUAL CALCULATION button was pressed, solution will be calculated as shown in Figure (9), total weight = 816.176 kg and total direct cost = 35372.9664 L.E. These results are 100% compatible with the hand written manual solution.

Hand Manual Calculation:

➢ Weight of one unit (Kg) =
[(1.2+1.2)×(2.1+2.1)×14.6]+[(1.2+1.2)×6×5.28]+[(2.1+2.1)×2 ×24.2] + [110.728+111.656+(2×83.656)] = **816.176 Kg**.

➢ Unit Cost of one unit in (L.E) =
[(1.2+1.2)×(2.1+2.1)×520.83]+[(1.2+1.2)×6×180]+[(2.1+2.1)× 2×300] + [6631+7200+(2×5590)] =**35372.9664 L.E**

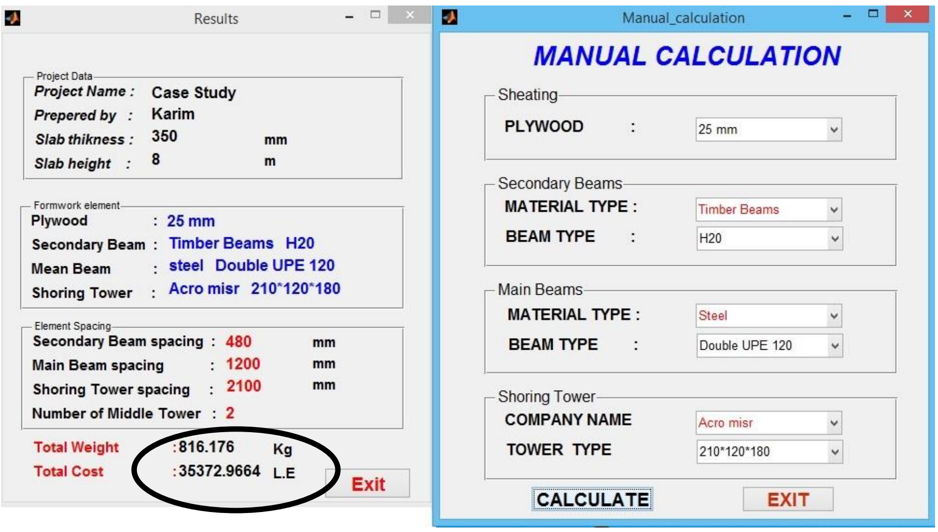

Figure (9): Manual calculation (FWSS results screen)

FWSS MODEL can find the optimum design solution by using the data base stored before by the user. If (GA weight) button was pressed, the optimizer tool will concentrate on searching on minimizing weight of formwork then calculate cost for modular unit of shoring tower. Figure (10) discusses a graph and result screen that shows the relationship between penalty value and generation. Penalty value represents the minimum formwork weight.

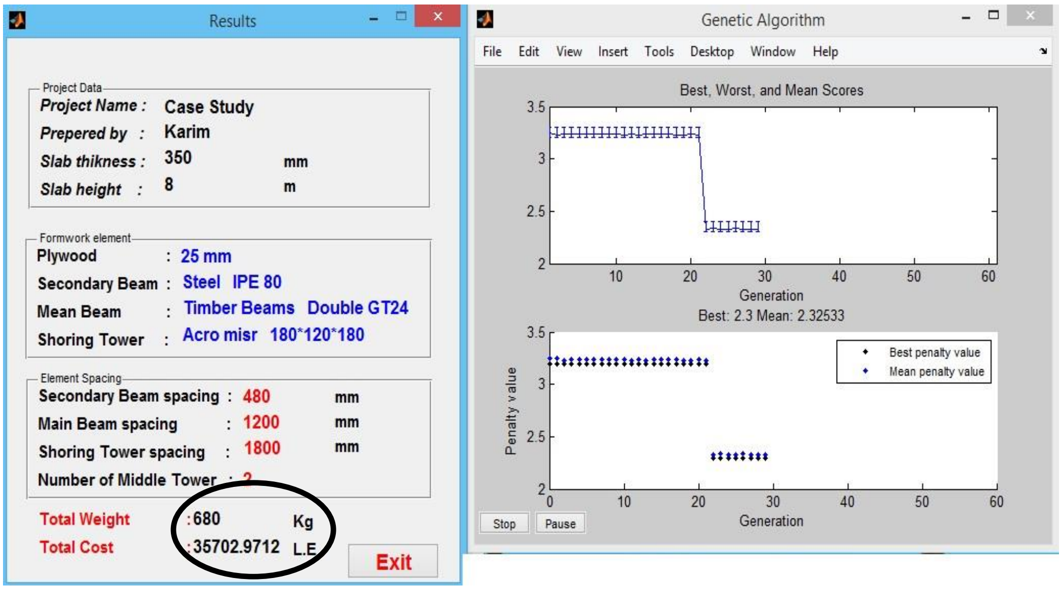

Figure (10): project optimum result based on (GA Weight as shown in the result screen and graph screen

By comparing the previous achieved results from both methods, the formwork system that is introduced by the FWSS MODEL optimizer is found less than the actual formwork system in weight by 136.176 kg, in cost by 330 LE with a minimizing ratio 16.68 % in weight and 0.93 % in cost. (GA Unit Cost) is another option tool in FWSS MODEL. User can use this tool as an optimizer tool to concentrate on minimizing direct cost for formwork then calculate weight for modular unit of shoring tower as shown in Figure (11).

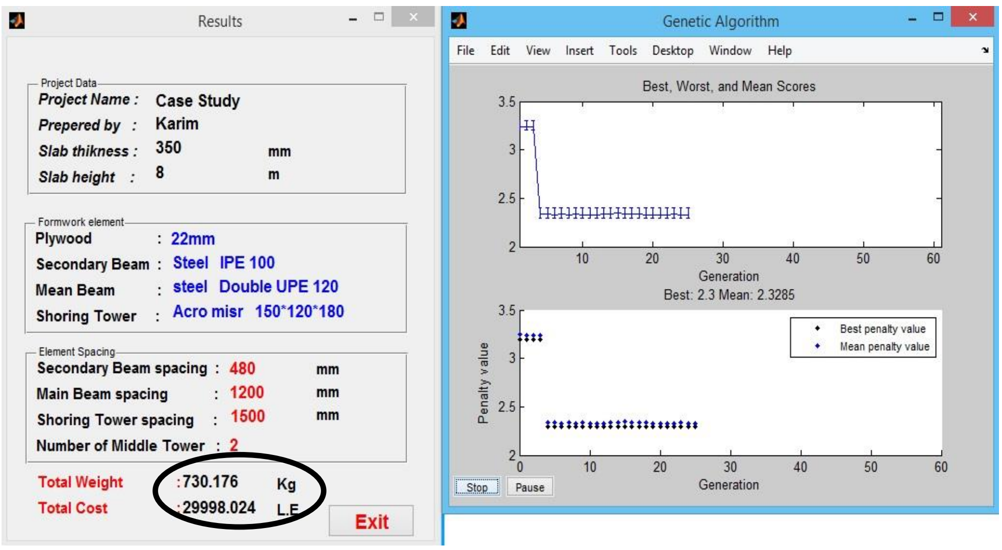

Figure (11): The project optimum result based on (GA Cost on the result screen and graph screen).

By comparing the previous achieved results, the formwork system that is introduced by the FWSS MODEL optimizer is found less than the actual formwork system in cost by 5374.94 LE, in weight by 86.176 Kg with a minimizing ratio 15.2 % in cost and 10.56 % in weight. Also, FWSS MODEL represents another optimization technique for users by pressing on (Optimal Solution) button, which is simple optimization for users as shown in Figure (12); outputs will be an optimum design solution which combined between weight and cost on formwork.

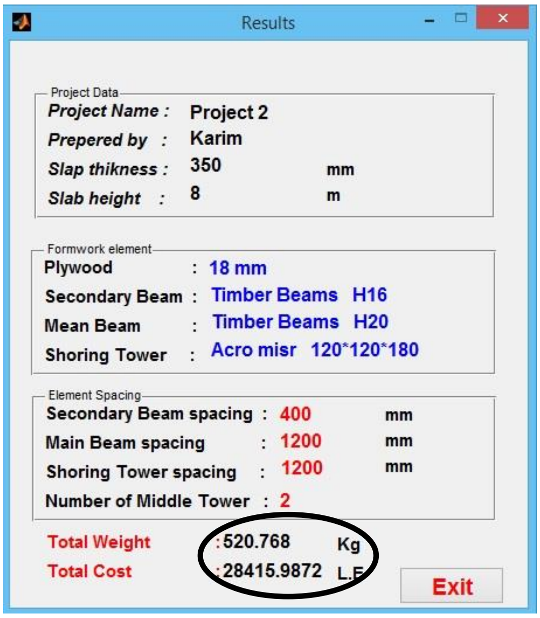

Figure (12) Simple optimizer solution

By comparing this achieved result by the MANUAL CALCULATION result, we get that this result is found less than the actual formwork system in direct cost by 6956.98 LE, in weight by 295.408 Kg with a minimizing ratio 19.67 % in cost and 36.2 % in weight. So, this ratio is for one unit area only and the proposed design is still satisfying all the design requirements. This result shows that the FWSS MODEL is actually leading to minimizing the formwork weight and direct cost.

7. Conclusion

A computer model (FORMWORK SELECTION SYSTEMS) called FWSS has been presented for determining the optimal design solution by calculating minimum weight and minimum cost for heavy and height reinforced concrete slab formwork system. FWSS designed to find the optimum design solution by using genetic algorithm as an optimizer technique. An example was analyzed to illustrate the use of the model and demonstrate its capabilities in optimizing formwork elements and generating optimal solution for minimizing weight and direct cost. This case study prove that the FWSS model succeeded in minimizing formwork weights and cost as it minimizing weight by 16.68% in case of (GA Weight), 10.56% in case of (GA Unit Cost), 36.2% in case of (Optimal Solution) and also minimizing cost by 0.93% in case of (GA weight), 15.2% in case of (GA Unit Cost) and 19.67% in case of (Optimal Solution).

Therefore, FWSS is easy to use because it depends on numbers of input and output screen made through MATLAB. FWSS is tested and use to solve any numerical example as shown before.

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