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OPTIMAL DESIGN OF PRESTRESSED CONCRETE HOLLOW CORE SLAB PANELS

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Abstract

The research has prepared programmed mathematical techniques by Visual basic language for analysis, design and calculating the optimization of precast prestress hollow core slab panels. The research deals with the optimization by adopting the modified Hooke-Jeevs method which is considered as a very suitable method especially for problems have many constraints. The formalizing of objective function was discussed according to required purpose. The aim of the study is to discuss three parameters (optimum weight, optimum cost and optimum live load). It is found that the average void percentage ratio regarding the optimum weight is about (50%) whereby the section tends to be in a shape where the voids become less than thickness and width take into consideration that the section is subjected to all the constraints (voids percentage tends to be much more than the regular case), as well as, it is found that the average of void percentage ratio concerning with the optimum cost is about (41%). The research also adopted preparing designable tables which are informative and easy in use practically for different kind of hollow core slab sections, it is found from the prepared maximum live load tables that the deflection restricts the span length not less than (60%), furthermore that adding topping slab (5cm) thickness increase the span length about (16-20) % for thicknesses (15-22) cm.

Keywords: Hollow Core Slab,Optimum Hollow Core Slab, Optimum Design

التصميم الامثل لالواح البلاطات الخرسانية المسبقة الجهد المجوفة

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الخـلاصـة

تناول البحث استخدام تقنيات رياضية برمجية بلغة فيجوال بيسك لتحليل وتصميم وحساب الامثلية لمقاطع البلاطات المجوفة المسبقة الصب المسبقة الجهد حيث تعرض البحث لدراسة الامثلية متبنيا الطريقة المعدلة لهوك- جيفس -Hooke Jeevs والتي تعتبر من الطرق المناسبة للمسائل المعرضة الى عدد كبير من المحددات او المقيدات. تم صياغة دالة الهدف بناءا على الغرض المطلوب حيث تم مناقشة تاثير ثلاثة عناصر و هي (الوزن الامثل ، الكلفة المثلى ، الحمل الحي الامثل). وتبين بان معدل نسبة حجم الفراغات (Voids) بالنسبة لمقاطع الوزن الامثل هي تقريبا (50%) حيث يميل المقطع ليكون بالشكل الذي تكون الفراغات مستنفذه اكبر مسافة من عرض وارتفاع المقطع مع الاخذ بنظر الاعتبار خضوع المقطع لجميع المقيدات (نسبة الفراغات تميل لتكون اكبر بكثير من الحالة الاعتيادية) ، ومن جهة اخرى اظهرت الدراسة بان معدل نسبة حجم الفراغات (Voids) بالنسبة لمقاطع الكلفة المثلى هي تقريبا (41%). البحث تبنى ايضا اعداد جداول تصميمية سهلة الاستخدام

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عمليا لمختلف انواع المقاطع حيث وجد عند اعداد جداول الاحمال الحية بان الانحناء (Deflection) يقيد من طول الفضاء بما لا يقل عن (60%) وان اضافة طبقة خرسانية (Topping slab) بسمك (5 سم) يزيد من امكانية زيادة طول الفضاء بمقدار (16- 20)% لسمك يتراوح بين (15-22) سم.

1. Introduction

Hollow core slab is a precast prestress concrete member having continuous voids as shown in Figure 1. This structural member had been produced for more than sixty years ago, it is fast started for spreading where they are currently become widely in use for all over the world Figure 2, and as an example of this, approximately 18 million square feet of hollow core slabs are produced annually across Canada.

Fig.1Hollow Core Slab with Circular Continues Void[11].

Fig.2 Usage of Hollow Core in Different Countries of World[14].

Hollow core slab is used in any type of building construction regardless the building size, height of building or the function of building. The present study adopt the optimum design of hollow core slab because there are so many variables of this structure and they have many solutions where the designers already search about the best solution (optimum solution).

2. Analysis and Design of Hollow Core Slab

It is very important for any structural optimization is to clarify the analysis and design to formalize the objective function and constraints. Concerning with analysis of hollow core slab, PCI (Precast/Prestress Concrete Institute) deals with hollow core slab as a simply supported beam but the present study make an investigation by analyzing it as isotropic plate by depending on Levy solution .Furthermore the present study adopts analysis of hollow core slab by considering it as anisotropic plate where an approximate equivalent plate that was adopted by Edward Ventsel [7] was used in present study as shown in Figure 3.

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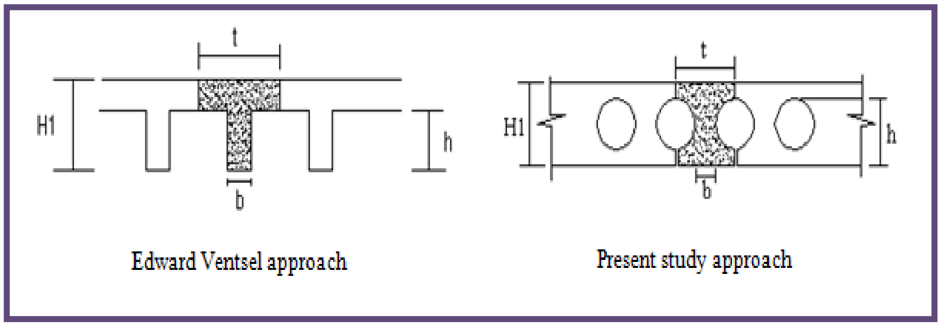

Fig.3 Equivalent Plate of Hollow Core Slab.

The final results of previous studies (Square plate & Poisson's ratio = 0.3) can be briefed in Table 1 as shown below:-

Table 1 Comparison among (PCI), Isotropic and Anisotropic Plate.

Case	Max deflection	Max moment	Max shear
PCI (simply supported beam)	$0.01302 \frac{wl^4}{EI}$	$0.125 \ wl^2$	$0.5 \ wl$
Simply supported isotropic plate	$0.01309 \frac{qa^4}{D}$	$0.1225 \ qa^2$	$0.4356 \ qa$
Simply supported anisotropic plate	$0.013054 \frac{qa^4}{D_x}$	$0.1252 \ qa^2$	$0.3493 \ qa$

It was concluded in previous studies that twenty cycles (loops) of expanding loading by Fourier series (Levy's method)(12) will be fair enough to be close to the exact solution as shown in Figure 4. Finally, it's normally in optimum design of hollow core slabs to use (PCI analysis) because the difference among the previous studies is not so high moreover that there is tendency in optimization to fix most of the parameters to see the behavior clearly.

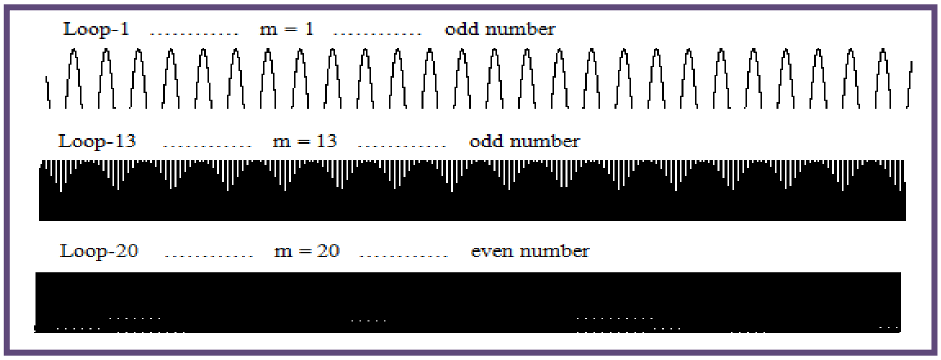

Fig.4 Expanding of Load by Fourier Series (Uniform Rectangular Load).

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Regarding the design of hollow core slab, it is general similar to the design of prestressed concrete members [6] .All the necessary design equations and requirements have been used as constraints of a problem where flexural strength design, shear design, deflection, stresses and the effect of topping slab have been taken into consideration. All of these equations will be clarified in optimization technique.

3. Optimization of Hollow Core Slab

3.1 General

Most of the design problems and studies have several solutions and the main topic for any design or study is how to obtain the best solution (optimum solution). Finding the optimum solution by classical seeking (try and error) among the variables is considered to be acceptable when less variables are considered while this method becomes invalid when the number of variables is large. The development in computers leads to an increase in the number of optimization methods where there are very large numbers but everyone has a limitation for its use. There is no general method available for solving all optimization problems efficiently.

3.2 Method of Optimization

There are many methods of optimization according to the type of problem but in all of the types of optimization methods, the design variables are modified to minimize or maximize the objective function. In (1961) Hook and Jeeves suggested direct-search method for optimization for an objective function without constraints[3], In (1984) Bunday modified this method where the method became to be in use for an objective function with constraints[4]. Hooke-Jeeves pattern search method and its modifying is adopted in present work. It can be briefed below:-

1- Suggest an initial value …..Checked with constraints
2- Make the first exploration …..Checked every step with the constraints
3- Make pattern move ….. Checked with constraints
4- Make the second exploration..... Checked every step with the constraints
5- Terminate the process when the step length has been reduced to a small value.

3.3 Formulation of the Problem

Hollow core slabs are one of the most structural forms that are widely in use in most of the world countries and any saving in that forms will reflect highly beneficial. As it is mentioned before that optimization is a body of mathematical results and numerical methods for finding maximization or minimization where that is according to the applications or the problem in the field. The present work will study three cases of optimization:-

1- minimum weight of hollow core slab
2- minimum cost of hollow core slab
3- maximum allowable live load

Construct the model-objective function and its constraints if it is available- is already depending on the purpose of the work. So the studying of minimum weight is considered informative if the field need for that kind of problem and so on for the minimum cost or maximum live load.

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3.3.1 Minimum Weight of Hollow Core Slab

The first important thing for any optimization is creating the objective function which is already related to the specific study that is wanted in researching. Here the objective function is very simple and it's clarified below:-

Weight = width * thickness * (1 - percentage voids ratio) * density

The other important thing for any optimization is the constraints that are limiting or restricting the objective function. Here the design constraints are all the equations that deal with flexure strength, shear, deflections, stresses and crack control. These variables will be discussed one by one.

3.3.1.1 Flexural Constraints

Below, the equations that are taken into consideration during the optimization process. The moment capacity of section is compared with that applied from the load:-
The notations in equations have been listed in notation list .

$$W_u = 1.2 * D.I + 1.6 * 1.1 \quad \text{.......... eq.(1)}$$

$$M_u = \text{coefficient} * w * l^2$$

a - Hollow core slabs as a rectangular section

$$M_u = .\phi.A_{ps}..f_{p.s}.\left(d_s - \frac{a}{2}\right) \quad \text{.......... eq.(2)}$$

$$a = .\frac{A_{ps}.f_{ps}}{0.85.f'_c.b} \quad \text{.......... eq.(3)}$$

b - Hollow core slabs as a flanged section

$$M_u = \phi\left\{A_{pf}..{}_{p.s}.\left(d_s - \frac{h_f}{2}\right).+A_{p.w}.f_{ps}\left(d_p - \frac{a}{2}\right).\right\} \quad \text{.......... eq.(4)}$$

$$A_{pw}.f_{ps}.= A_{ps}.f_{ps} - A_{pf}.f_{ps} \quad \text{.......... eq.(5)}$$

$$a = .\frac{A_{pw}.f_{ps}}{0.85.f'_c.b_w} \quad \text{.......... eq.(6)}$$

To ensure that prestressed concrete is over loaded which will have a ductile response before failure, it is important to put an upper limit to the tensile steel ratio:-

$$\omega_p = \rho_p \cdot \frac{f_{ps}}{f'_c}$$

if $\omega_p > 0.32\ \beta_1$ then

$$M_n = .f'_c.b.d^2 p\left(0.32B_1 - 0.08B_1^2\right) \qquad a \le h_f \quad \text{.......... eq.(7)}$$

$$M_n = .f'_c.b_w.d^2 p\left(0.32B_1 - 0.08B_1^2\right) + 0.85 f'_c\left(b - b_w\right)h_f\left(dp - \frac{h_f}{2}\right) \qquad a \succ h_f \quad \text{.......... eq.(8)}$$

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For any case, total amount of prestressed reinforcement shall be adequate to develop a factored load at least (1.2) times the cracking load computed on the basis of the modulus of rupture (f_r) as shown below:-

$$\emptyset M_n \geq 1.2 * M_{cr}$$

$$M_{cr} = \left(\frac{P_e}{A_c} + \frac{P_e.e}{S_b} + f_r\right).S_b \text{..........} eq.(9)$$

Concerning the flexural constraints, the moment capacity of section should be not less than the moment due to the applied load, taking into consideration the steel ratio (steel index) and (M_{cr}).

3.3.1.2 Shear Constraints

The shear capacity of section is the less of the results of the two equations (V_{ci}) and (V_{cw})

$$V_{ci} = 0.05\lambda\sqrt{f'_c}\, b_w.d_p + V_d + \frac{V_i.M_{cre}}{M_{max}} \text{..........} eq.(10)$$

d_p need not be taken less than (0.8 h).

V_i, M_{max} are calculated from the externally applied factored loads which include superimposed dead load and live load.

$$M_{cre} = \left(\frac{I}{y_t}\right)\left(0.5\lambda\sqrt{f'_c} + f_{pe} - f_d\right) \text{..........} eq.(11)$$

V_{ci} it should be not less than ($0.17\,\lambda\sqrt{f'_c}\,b_w.\,d$)

$$C_{cw} = \left(0.29\lambda\sqrt{f'_c} + 0.3 f_{pc}\right) b_w.d_p + V_p \text{..........} eq.(12)$$

The shear that is applied from the load:-

$$w_u = 1.2 * D.l + 1.6 * l.l$$

$$V_u = \text{coefficient} * w * l$$

Shear capacity of section should be not less than the shear that is applied from the loads [6].

3.3.1.3 Deflection Constraints

$$Intial\,camber = \frac{p.e.L^2}{8\,EI} - \frac{5\,w.L^4}{384\,EI} \text{..........} eq.(13)$$

$$Erection\ \ camber = \left(\frac{p.e.L^2}{8\,EI} * 1.8\right) - \left(\frac{5\,w.L^4}{384\,EI} * 1.85\right) \text{..........} eq.(14)$$

Where

P = initial prestressed force

e = eccentricity

L =span length

w =self weight of hollow core slab

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As it was mentioned before that the long term camber can be calculated by using multiplier table as clarified below:-

$$Final\ camber = \left(\frac{p.e.L^2}{8\ EI} * 2.45\right) - \left(\frac{5\ w.L^4}{384\ EI} * 2.7\right) \text{.......} eq.(15)$$

$$Intial\ deflection\ dueto\ dead\ load = \frac{5\,(D.I).L^4}{384\ EI} \text{.......} eq.(16)$$

$$Final\ deflection\ dueto\ live\ load = \frac{5\,(1.1).L^4}{384\ EI} * 3 \text{.......} eq.(17)$$

$$Intial\ deflection\ dueto\ live\ load = \frac{5\,(1.1).L^4}{384\ EI} \text{.......} eq.(18)$$

ACI code (9.5.4.1) permitted to use the moment of inertia of the gross concrete section for class (U) flexural member. For comparison with ACI code, when non-structural elements are attached to the slabs, the portion of deflection after erection will be equal to (Change in camber + final defection +initial live load) where change in camber equal to (final camber – erection camber) (6). Comparison with Table 9.5(b) of the ACI Code is used during the process of optimization.

3.3.1.4 Stresses Constraints

Stresses in concrete immediately after prestress transfer (before time-dependent prestress loss) at the end of support are:

$$f_{top} = -\frac{P_1}{A_c} . + \frac{P.e.C_1}{I_c} \text{.......} eq.(19)$$

$$f_{bot} = -\frac{P_1}{A_c} + \frac{P.e.C_2}{I_c} \text{.......} eq.(20)$$

The permissible extreme fiber stress in compression at ends of simply supported member shall not exceed (0.7 f_{ci})

Stresses in concrete immediately after prestress transfer (before time-dependent prestress loss) at the mid of support are:

$$f_{top} = -\frac{P_1}{A_c} + \frac{P.e.C_1}{I_c} - \frac{M_0}{S_1} \text{.......} eq.(21)$$

Where :

$S_1 = \frac{I_c}{C_1}$, $S_2 = \frac{Ic}{C_2}$

The extreme fiber stress in compression at mid span of simply supported member shall not exceed (0.6 f_{ci}). Stresses in concrete due to prestress and (dead & live) load after allowance for all prestress losses are:

$$f_{top} = -\frac{P_1}{A_c} + \frac{P.e.C_1}{I_c} - \frac{M_0}{S_1} - \frac{M_S}{S_1} \text{.......} eq.(22)$$

Kufa Journal of Engineering (K.J.E)
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Vol. 5, Issue 1, Dec., 2013,P.P.33-50
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$$f_{bot} = -\frac{P_1}{A_c} + \frac{P.e.C_2}{I_c} \cdot \frac{M_0}{S_2} - \frac{M_s}{S_2} \quad \text{......} eq.(23)$$

Where:
$M_{\circ}$ = moment due to service load
M_s = moment of D.L + moment of L.L

The permissible compression stresses under the prestress plus total load shall not exceed (0.6 f'_c). The prestress member shall be classified as class (U), class (T), class (C) based on (ft - which is meaning the tensile strength concrete) as briefed below:-

Class U: $ft \le 0.62\sqrt{f'_c}$
Class T: $0.62\sqrt{f'_c} < ft \le 1.0\sqrt{f'_c}$
Class C: $ft > 1.0\sqrt{f'_c}$

Hollow core slabs are normally designed to be uncracked section under full service load (class U)(6) so there is no need for requirements of crack control. Finally, the dependent design variables that are used in this problem is the (width, thickness of hollow core slab, diameter of void), the other variables are used as a given value. Briefing of minimum weight problem is plotted in Table 2.

Table 2 Optimization-Minimum Weight.

Minimum weight of hollow core slab	
Objective function	Weight = width * thickness * void percentage * density
Constraints	Flexure, Shear, Deflection, Stresses
Design variables	1- Width , Thickness 2- Width , Thickness, diameter
Method of optimization	Modified Hooke-Jeeves

3.3.2 Minimum Cost of Hollow Core Slab

The same procedure has been done but for calculating the minimum cost where the equations of constraints are similar to those mentioned previously. The objective function and constraints are briefed as mentioned in Table 3.

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Vol. 5, Issue 1, Dec., 2013,P.P.33-50
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Table 3 Optimization-Minimum Cost.

Minimum cost of hollow core slab	
Objective function	$a = Aps * L * Dens * Cs$ $b = \left\{B * H - \left(N * D^4 * \frac{\pi}{4}\right)\right\} * L * Cc$ $c = B * L * Csf$ $Obj.fun. = a + b + c$
Constraints	Flexure, Shear, Deflection, Stresses
Design variables	Aps H D N
Method of optimization	Modified Hooke-Jeeves

3.3.3 Maximum Allowable Live Load

According to the mathematical point of view, optimization is a maximum or minimum value where it may be obtained after a searching among some of overlapping phases (governing equations) that are related to the problem. Here, the maximum allowable live load is added to the optimization idea because the problem deals with the maximization. The optimized body can be expressed as below:

Objective function:

$\text{Max}_{\text{L.L}}$ = Min ($\text{L.L}_{\text{"flexure"}}$, $\text{L.L}_{\text{"shear"}}$, $\text{L.L}_{\text{" deflection"}}$, $\text{L.L}_{\text{" stresses"}}$)

Where L.L = live load which was obtained by using the same equations that are mentioned previously in article (3.3.1).

Constraints:-

Maximum live load should be not less than zero and from the practical view, the live load under (0.5 kN/m^2) is considered non informative.

Briefing of maximum live load problem is plotted in Table 4:-

Table 4 Optimization-Maximum Live Load.

Maximum live load	
Objective function	$Max\ L.L = Min(L.L\ flexure, L.L\ shear, L.L\ deflection, L.L\ stresses)$
Constraints	$L.L \geq 0.5\ kN/m^2$
Design variables	Span length, reinforcement
Method of optimization	Classical searching

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4. Application

As it is mentioned before and according to the field requirements, the optimum weight, cost and live load can be found as shown below:-

For a given data:-

Density :- 24 kN/m^3 | F_c' = 35 MPa | L.L = 5 kN/m^2
F_{py} = 1500 MPa | F_{pu} =1662 MPa | Length = 3 m
Losses = 15 % | Max deflection = 1 cm | Area of steel = 187 mm^2
Number of voids =7 | Diameter = 0.1 m

Regarding optimum weight, there is relationship between diameter of void and the dependent variables where the decreasing in diameter causes direct effect along the width moreover the thickness regardless the geometric and practical considerations. The optimum weight can be obtained by choosing the optimum thickness and optimum width according to different cases of length as shown in Figures 5, 6 and 7.

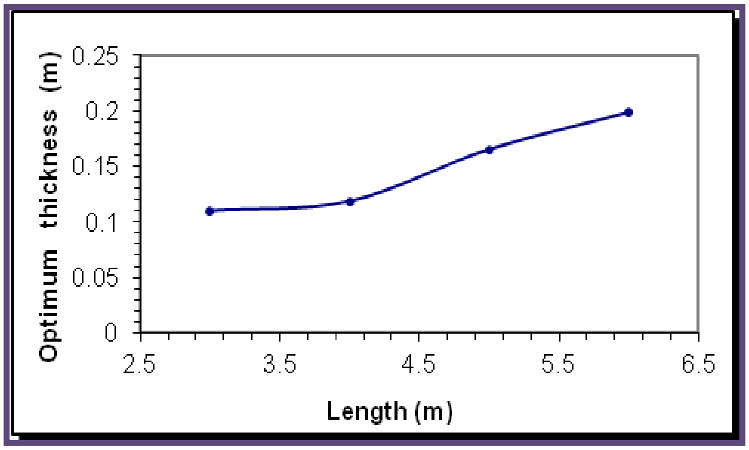

Fig.5 Optimum Thickness.

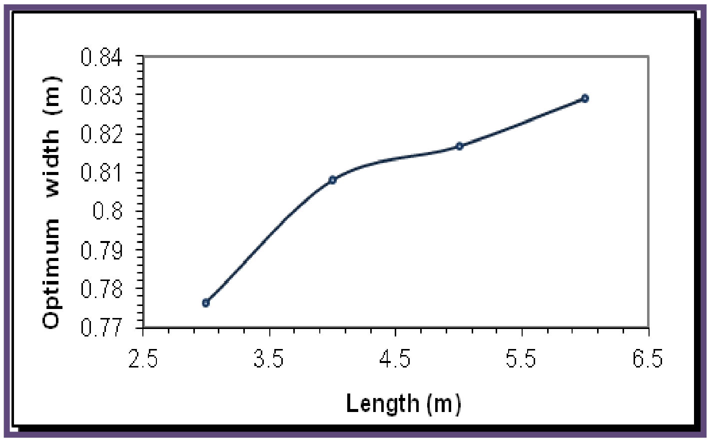

Fig.6 Optimum Width.

Kufa Journal of Engineering (K.J.E)
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Vol. 5, Issue 1, Dec., 2013,P.P.33-50
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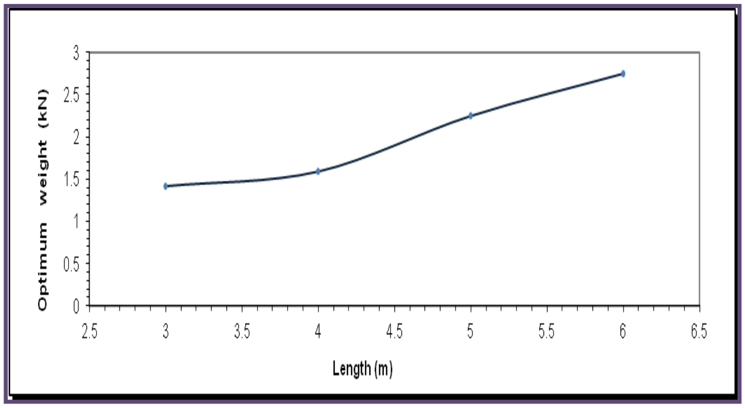

Fig.7 Optimum Weight.

Just for a theoretical study, the tendency of optimization is decreasing along reducing the void diameter. When the diameter is taken as variable the optimum case can be shown in Table 5.

Table 5 Optimum Weight uses the Diameter as a Variable.

Optimum thickness	Optimum width	Optimum diameter	Optimum weight
0.0637989	0.19369659	0.02320	0.2897023

Briefly, the diameter of voids and its number tend to be maximum as possible to get the minimum weight.

- Concerning with optimum cost, it can be obtained by finding (optimum area steel, optimum thickness, optimum void diameter, optimum number of voids) as shown in Figures(8,9,10 and 11).

Kufa Journal of Engineering (K.J.E)
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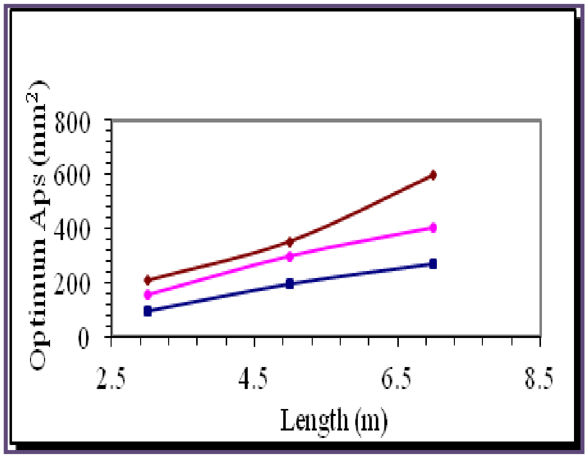

Fig.8 Optimum Area Steel.

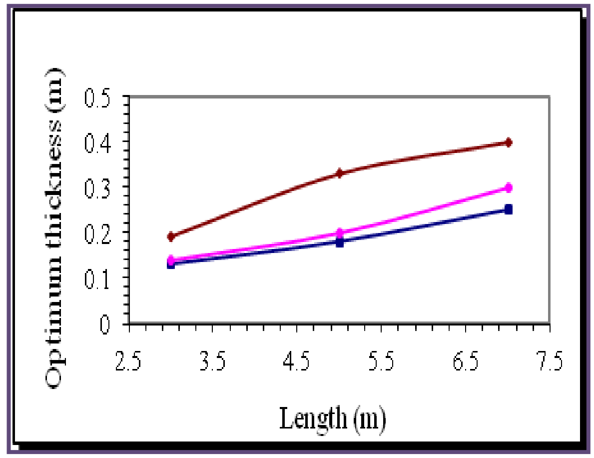

Fig.9 Optimum Thickness.

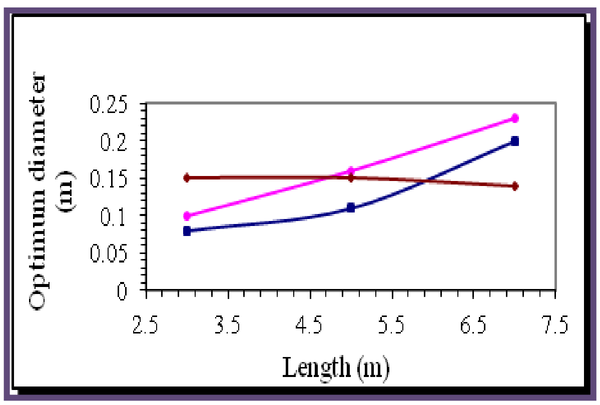

Fig.10 Optimum Void Diameter.

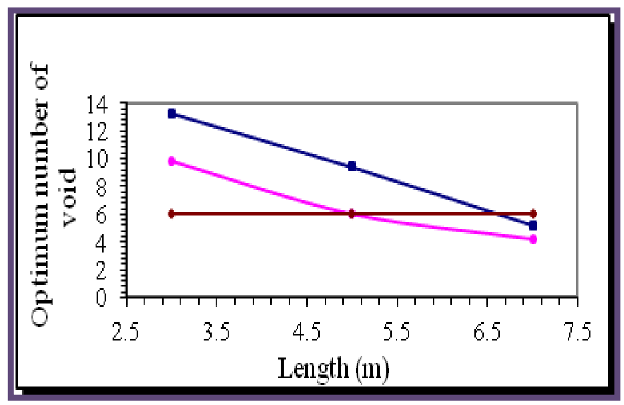

Fig.11 Optimum Number of Voids.

It is clear from the above figures that the optimum area of steel and thickness vary regularly among different cases of lengths and live loads while there is an overlapping among the optimum diameter and number of voids due to the direct relation between them. The above charts can be used for finding the optimum design variables to get the optimum cost where these charts are produced for the most common lengths and live loads in the field.

- Regarding the maximum live load and according to Table 4, the maximum live load is clarified below. For a given data:

Density of concrete: 24 kg/m^3 ,F_{pu} = 1662 MPa , F_{py} = 1500 MPa F_c' = 35 MPa

Max deflection = Length / 480

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The effect of topping slab will be taken into consideration where it will be plotted with the (charts without topping) to clarify the behavior and to make visible comparison. The properties of topping slab are as shown below:-

Topping slab thickness = 5 cm , F_c'= 35 MPa,Other data: will be mentioned later on.

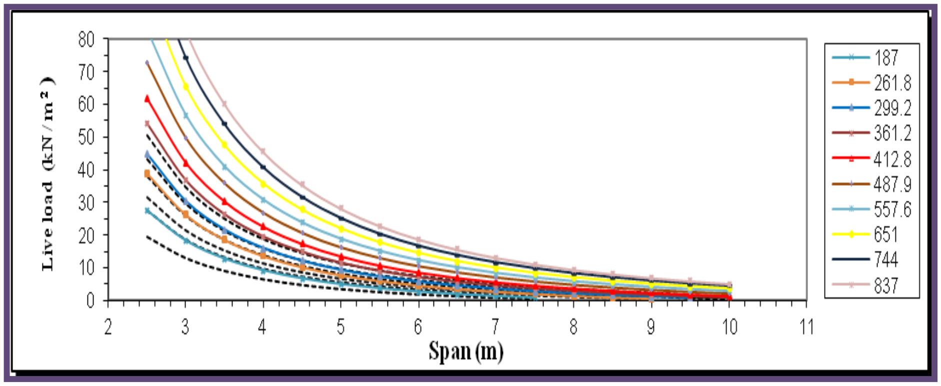

Fig.12 Live Load- Span Relation due to Flexural Condition (with Topping).

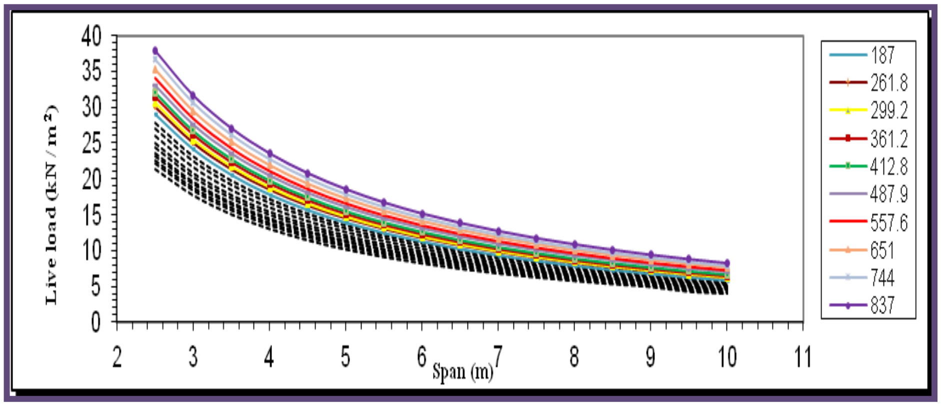

Fig.13 Live Load- Span Relation due to Shear Condition (with Topping).

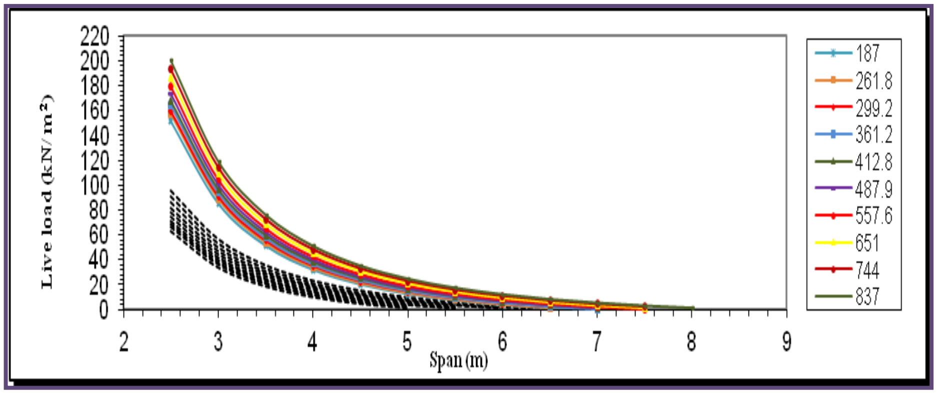

Fig.14 Live Load-Span Relation due to Deflection Condition (with Topping).

Kufa Journal of Engineering (K.J.E)
ISSN 2207-5528
Vol. 5, Issue 1, Dec., 2013,P.P.33-50
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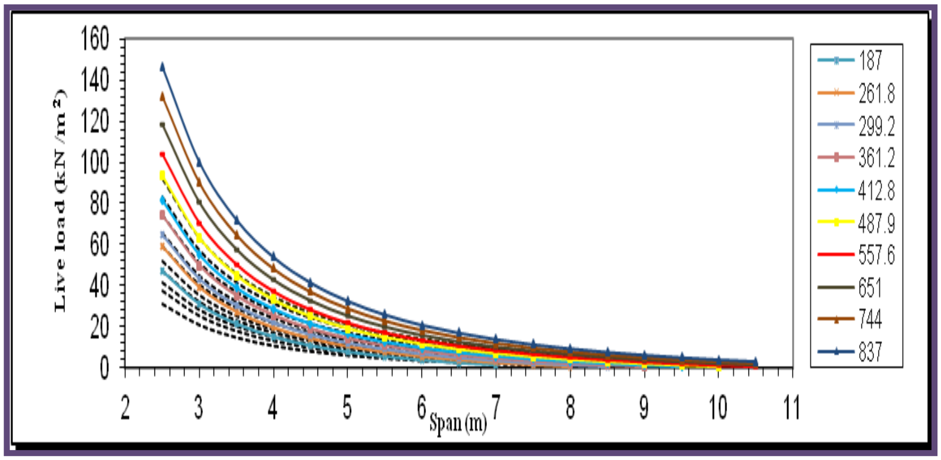

Fig.15 Live Load- Span Relation due to Allowable Stress Condition (with Topping).

* Note: Dashed curves related to the hollow core slabs without topping

So the maximum allowable live load for any given data (In case of hollow core slabs, thickness = 15 cm, number of voids = 8 and diameter of void = 105mm) can be found by using the minimum of the curves that shown in Figures (12, 13, 14 and 15). Unique curve cannot be plotted because of the varying of the governing phases during changing the length and area of steel. Unique table is prepared where it covers all the phases (flexure, shear, deflection and stresses), so the maximum live load for different cases of length and prestressed reinforcement is clarified in Table 6 and 7.

Table 6 Maximum Live Load due to all Condition (Case without Topping).

H.C.S – precast, prestress / (0.15 cm) thickness, (1.2 m) width, (8) voids/ (0.105m) diameter										
Maximum live load (kN/m^2)…..due to flexure, shear, deflection and stresses										
As (mm^2)	187	261.8	299.2	361.2	412.8	487.9	557.6	651	744	837
Span (m)										
2.5	19.54	22.12	22.49	23.11	23.63	24.38	25.07	26.01	26.93	27.86
3	13.06	18.37	18.68	19.20	19.64	20.27	20.85	21.64	22.42	23.20
3.5	9.16	13.28	15.30	16.36	16.73	17.28	17.78	18.46	19.14	19.81
4	6.62	9.77	11.32	13.73	14.52	15.00	15.45	15.99		
4.5	4.88	6.18	6.77	7.75	8.56	9.75	10.85	12.28		
5	1.57	2.52	3.01	3.80	4.46	5.42	6.31	7.51	8.69	9.63
5.5				1.09	1.63	2.43	3.16	4.15	5.13	6.12
6							0.89	1.72	2.54	3.37
6.5									0.62	1.32

Kufa Journal of Engineering (K.J.E)
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Vol. 5, Issue 1, Dec., 2013,P.P.33-50
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* Shadow cells means that increasing the reinforcement is considered non informative due to the limitation of steel index

Table 7 Maximum Live Load due to All Condition (Case with Topping).

H.C.S – precast, prestress / (0.15 cm) thickness, (1.2 m) width, (8) voids/ (0.115m) diameter								Topping - 5cm	
Maximum live load (kN/m^2)										
As (mm^2)	187	261.8	299.2	361.2	412.8	487.9	557.6	651	744	837
Span (m)										
2.5	22.48	23.39	23.84	24.60	25.22	26.14	26.99	28.12	29.25	30.38
3	18.46	19.41	19.79	20.43	20.96	21.73	22.45	23.41	24.37	25.32
3.5	12.94	16.48	16.82	17.38	17.82	18.50	19.12	19.95	20.78	21.61
4	9.36	13.88	14.55	15.04	15.45	16.03	16.57	17.30	18.04	18.77
4.5	6.90	10.47	12.24	13.20	13.56	14.09	14.58	15.23	15.88	16.54
5	5.14	8.03	9.46	11.71	12.04	12.51	12.95	13.55	14.14	14.73
5.5	3.84	6.23	7.41	9.34	10.78	11.21	11.62	12.16	12.69	13.23
6	2.85	4.86	5.85	7.47	8.80	10.11	10.49	10.99	11.48	11.98
6.5	2.08	3.80	4.63	6.02	7.15	8.77	9.53	10.00	10.45	10.91
7	1.47	2.95	3.68	4.87	5.84	7.24	8.51	9.14	9.57	9.99
7.5	0.70	1.99	2.63	3.70	4.59	5.88	6.62	7.41	8.19	8.99
8		1.13	1.71	2.65	3.16	3.72	4.24	4.94	5.63	6.33
8.5			0.65	1.06	1.41	1.90	2.36	2.98	3.59	4.21
9							0.85	1.40	1.95	2.50
9.5									0.61	1.11

Different tables have been produced for different sections of hollow core slab to be available for any future studies or designs.

5. Conclusions

The following conclusions can be drawn:

1- Precast / prestressed concrete institute (PCI) uses the coefficients that are related to the beam analysis in the analysis of hollow core slabs while the present study found by using Levy's method for the analysis of isotropic plate :-
   a- Twenty cycles in Fourier expansion is enough to be near the exact value.
   b- The average percentage ratio differences between Levy and (PCI) results are about (0.6%, 23%, 2.7%) for moment, shear and deflection respectively. Taking into consideration that it is normal to use (PCI) coefficients in optimum design of hollow core slab.

2- The average percentage voids ratio to get minimum weight is about (50%) where the minimum weight of hollow core panel is obtained by depending on the void diameter. The thickness of hollow core panel will be a little bit larger than the diameter (for just satisfying the practical and geometrical consideration which is equal to 2.75 cm in each face).From other

Kufa Journal of Engineering (K.J.E)
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Vol. 5, Issue 1, Dec., 2013,P.P.33-50
Printed in Iraq

side the width will be larger than the "diameter of void multiplying by the number of voids" where minimum distance between two voids is 2.75 cm. In addition to that, it is recommended to use width less than (1.2m) in spans less than (5 m) to get minimum weight.

3- It is found from optimum cost of hollow core slabs that:-
  a- General charts can be used for finding the optimum design variables to get the optimum cost.
  b- The average percentage voids ratio is about (41%) where the diameter of void tend to be less than the thickness by a little bit distance
  c- In General, thickness, area of prestressed steel and diameter of void tend toward increasing along increasing the length and live load while the number of voids are decreased.

4- Modified Hooke-Jeevs method is considered very suitable method for the problems that have large number of constraints where it is very easy for programming and for connecting the constraints with the problem. From other side the method is not able to move along the constraint and converges on the first point on the constraint it locates as the solution so searching along the initial variable has to be done to avoid that problem.

5- Concern finding the maximum live load, three main points are recorded:-
  a- Many tables for available productions have been prepared to be informative for any work or study. The tables have been covered all the requirements (flexure, shear, deflection, stresses).
  b- The governing equation for the last three rows for all the tables of max live load is the deflection, from other side the deflection is restricting the span length to be not less than (60%) for any table of any section of hollow core slab.
  c- Adding topping slab (5cm) increases the span lengths in the tables as it is briefed below:-

Hollow Core Slab Thickness (cm)	Span Length Increasing
15 - 22	16% - 20%
25 - 32	8% - 14%
40 - 50	3% - 8%

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Notations

A_{ps} = Area of prestressing reinforcement
A_{pf} = Area of prestressing reinforcement equivalent to flange
A_{pw} = Area of prestressing reinforcement equivalent to web
Ac = Area of concrete in hollow core slab
a = Length used for plate
b_w = Net web width of hollow core slab
C_1 = Distance from centroid axis to top extreme fiber
C_2 = Distance from centroid axis to bottom extreme fiber
Cs = Cost of prestress steel
Cc = Cost of concrete
Csf = Cost of slip former
dp = Distance from extreme compression fiber to centroid of prestressed reinforcement
D, D_x = Flexural rigidity of the plate
D.l = Dead load
E = Modulus of elasticity of concrete
e = Distance from neutral axis to centroid of prestressed reinforcement
fc' = Specified design compressive strength of concrete
f_{ci} = Compressive strength of concrete at the time of initial prestress
f_{pc} = Compressive stress in concrete at the centroid of the section due to effective prestress for non-composite sections or due to effective prestress and moments resisted by the precast section alone for composite sections.
f_{py} = Specified yield strength of prestressing steel

Kufa Journal of Engineering (K.J.E)
ISSN 2207-5528
Vol. 5, Issue 1, Dec., 2013,P.P.33-50
Printed in Iraq

f_{pe} = Compressive stress in concrete at extreme fiber where external loads cause tension due to the effective prestress only
f_{ps} = Stress in prestressed reinforcement at nominal strength
f_{pu} = Specified tensile strength of prestressing steel
fr = Modulus of rupture of concrete
hf = Depth from the face of hollow core slab down to top level of voids
Ic = Moment of inertia of hollow core slab
l.l = Live load
L = length of hollow core slab
Mn = Nominal flexure strength
Mu = Factored design moment
M_{cr} = Cracking moment
Pi = Initial prestress force after jacking losses
p_e = Effective prestress force after all losses
ρ_p = Ratio of prestressing reinforcement
S_b = Elastic section modulus
V_{ci} = Nominal shear strength of concrete in a shear-flexure failure mode
V_{cw} = Nominal shear strength of concrete in a web shear failure mode
V_d = shear due to unfactored self weight
Vp = Vertical component of effective prestress force
yb = Distance from neutral axis to extreme bottom fiber
yt = Used as either distance to top fiber or tension fiber from neutral axis
w = Weight per meter length
Wu= design load
q = weight per meter length for a plate
$\emptyset$ = ACI strength reduction factor
γp = Factor for type of prestressing strand
λ = Factor depend on the concrete type
ωp = Prestressing reinforcement index