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Optimum design of irregular grillage systems using CSS and ECSS algorithms with different boundary conditions

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Abstract

In this research, the Charged System Search (CSS) and Enhanced Charged System Search (ECSS) algorithms are used to obtain the optimum design of irregular grillage systems with different spacing and various boundary conditions. The cross-sectional properties of the beams are selected as the design variables and the weight of structure is used as the objective function. The displacement limitations and permissible stress constraints are employed from LRFD-AISC and are considered in the formulation of the design problem. Furthermore, in obtaining the response of the grillage systems, the effect of warping is also taken into account. The comparison of the results shows that warping changes the beam spacing, and different boundary conditions have substantial effects on the optimum design of irregular grillage systems.

Keywords: *Irregular grillage systems, optimization, CSS algorithm, enhanced CSS algorithm, warping effect, warping.*

1. Introduction

Grillage systems are extensively used in different structures such as bridge decks, ship hulls, decks, airplane wings, building floors, overhead water tanks slabs and specifically in the roof of big areas where no columns are used. Grillage systems have some advantages over other types of roof systems, including: (i) it is possible to build more beautiful structures using grillage systems, (ii) these are very efficient in transferring concentrated loads and in having the entire structure to participate in the load carrying action.

Depending on the type of the structure, grillage systems can be regular or irregular. Regular grillages are frequently used in different type of structures. However, the performance limitations of building a structure sometimes make the designer to model the systems in irregular form. Utilization and optimization of the irregular grillages seems to be necessary if, for instance, there is opening in part of a grillage structure, the loads applied on the grillage are agglomerated in a specific area or when the boundary conditions do not allow arranging a fulcrum. In order to optimize an irregular grillage system, it is important to use a method which can solve the optimization problem precisely and in a reasonable time. For this reason, meta-heuristic algorithms are employed to find desirable regions in the search space in an affordable time. These algorithms reduce the effective size of the search space and explore that space efficiently. Different meta-heuristics algorithms have been introduced in the last decades for structural optimization among which the followings have been used more frequently: Genetic Algorithm (GA) which was introduced by Holland [1] is one of the most famous algorithms which are inspired by Darwin theory. Particle Swarm Optimization (PSO) is another optimization method introduced by Eberhart and Kennedy [2] and is based on the social behavior of birds. Ant Colony Optimization (ACO) proposed by Dorigo et al. [3] is another population-based optimization technique which simulates the behavior of the ants when they try to find the shortest route from nest to food and vice versa. Another meta-heuristics optimization method is Harmony Search (HS) that was given by Geem et al. [4]; this method imitate natural musical performance routine that come to mind when a musician searches for a better state of harmony. Erol and Eksin [5] introduced the big bang-big crunch algorithm (BB-BC) which is based on big bang-big crunch theory, one of the theories of the universe evolution. The Standard Charged System Search (CSS) algorithm and Enhanced Charged System Search (ECSS), inspired by the governing laws of electrostatics in physics and the governing laws of motion from the Newtonian mechanics has been recently introduced by Kaveh and Talatahari [6,7,8] and applied to different types of structure [9,10] as an efficient method for

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optimization of structures. The CSS uses a number of solution candidates which are called charged particles (CPs). Each CP is treated as a charged sphere and it can exert an electrical force on the other agents according to the Coulomb and Gauss laws of electrostatics. The resulting force accelerates each CP according to Newton's second law. Finally, using Newtonian mechanics, the position of each CP is determined at any time based on its previous position, velocity and acceleration in the space [7]. In the ECSS, the concept of the FOF (Fields of Forces) model, from physics that explain the reason of the operation of the universe, is used to improve the performance of the CSS algorithm. In fact, the discrete time concept in CSS algorithm is replaced by a continuous time changing. This substitution enhances the efficiency of the CSS algorithm [7].

The purpose of an optimization study is minimizing or maximizing the values of some selected variables. Cross-sectional properties of beams are one of the effective variables in designing grillage systems because they are correlated with the weight of the structure and by reducing the cross-sectional areas the weight of the grillage is reduced. In this context, the response of the system to external loading must be within the criteria defined by LRFD-AISC code [11].

Analysis of grillage systems can be performed with or without considering the warping effect. Since warping plays an important role in the analysis of the grillage systems and makes the optimum design more realistic, it is recommended to consider it in the analysis.

In this paper, the optimum design of irregular grillage systems is carried out. Cross sectional properties of beams are selected as variables and the weight of the structure is selected as the objective function of the optimization. In addition to optimize the cross-sectional properties of beams, the impacts of using different spacing of the beams and various conditions of the supports on the objective function are also investigated. The effect of warping is also taken into account in the analysis of the grillage system. Moreover, the results of the analysis obtained by considering warping effect are compared to those when warping is ignored. The CSS and ECSS algorithms are utilized as the optimization tools and their capability are compared.

2. Methodology

2.1. Mathematical statement of optimum design problem

The optimum design of a grillage system consists of finding the values of the cross-sectional areas corresponding to minimum weight of the structure. This can be expressed as:

$$\begin{aligned}&\text{Find} \quad A=[A_1, A_2,\dots,A_{ng}]\\&A_i \in D_i\\&\text{to minimize} \quad W(A)=\sum_{i=1}^{nm}\gamma_i.A_i.l_i\end{aligned} \tag{1}$$

Where X is the set of design variables (the cross section areas of the beams); n is the number of member groups; S is the set of permissible value of variable A_i which is the set of 272 W-sections as given in LRFD-AISC [11]. $W(A)$ is the total weight of the grillage system; nm is the number of all elements in the structure; ρ_i is the density of the member i and l_i is the length of member i.

2.2. The CSS Algorithms

2.2.1. The standard charged system search

The standard CSS algorithm is a recent meta-heuristic algorithm that was introduced by Kaveh and Talatahari [6]. This algorithm is based on the governing Coulomb law from electrostatic of physics and the Newtonian law of mechanics.

The magnitude of the electric field E_{ij} at a point outside and inside a sphere of radius "a" is defined respectively as [12]:

$$\begin{cases} E_{ij}=k_e\dfrac{q_i}{r_{ij}^2} & : r_{ij}\ge a\\[2ex] E_{ij}=k_e\dfrac{q_i}{a^3}r_{ij} & : r_{ij}<a\end{cases} \tag{2}$$

Where k_e is the Coulomb constant; r_{ij} is the separation of two charged particles; q_i is the magnitude of the ith charged particle.

Using the principle of superposition, the resulting electric force due to N charged spheres is equal to [6]:

$$\begin{gathered}\mathrm{F}_{ij}=k_e q_j\sum_{i,i\neq j}\left(\frac{q_i}{a^3}r_{ij}.i_1+\frac{q_i}{r_{ij}^2}.i_2\right)\frac{\mathrm{r}_i-\mathrm{r}_j}{\left\|\mathrm{r}_i-\mathrm{r}_j\right\|}\\ \begin{cases} i_1=1, i_2=0 \Leftrightarrow r_{ij}<a\\ i_1=0, i_2=1 \Leftrightarrow r_{ij}\ge a\end{cases}\end{gathered} \tag{3}$$

Also, according to the Newtonian mechanics, we have [6]:

$$\begin{aligned}&\Delta\mathrm{r}=\mathrm{r}_{new}-\mathrm{r}_{old}\\&\mathrm{v}=\frac{\mathrm{r}_{new}-\mathrm{r}_{old}}{t_{new}-t_{old}}=\frac{\mathrm{r}_{new}-\mathrm{r}_{old}}{\Delta t}\\&\mathrm{a}=\frac{\mathrm{v}_{new}-\mathrm{v}_{old}}{\Delta t}\end{aligned} \tag{4}$$

Where r_{old} and r_{new} are the initial and final positions of the particle, respectively; v is the velocity of the particle; and "a" is the acceleration of the particle. Combining the above equations and using Newton's second law, the displacement of any object as a function of time is obtained as

$$\mathrm{r}_{new}=\frac{1}{2}\mathrm{a}.\Delta t^2+\mathrm{v}_{old}.\Delta t+\mathrm{r}_{old} \tag{5}$$

Inspired by the above electrostatic and Newtonian mechanics laws, the pseudo-code of the CSS algorithm is presented as follows [6]:

Level 1: Initialization

Step 1. Initialization. Initialize the parameters of the CSS algorithm. Initialize an array of charged particles (CPs) with random positions. The initial velocities of the CPs are taken as zero. Each CP has a charge of magnitude (q) defined considering the quality of its solution as:

$$q_i=\frac{\mathrm{fit}(i)-\mathrm{fitworst}}{\mathrm{fitbest}-\mathrm{fitworst}}, \qquad i=1,2,\dots,N \tag{6}$$

Where fitbest and fitworst are the best and the worst fitness of all the particles; fit (i) represents the fitness of the ith agent.

The separation distance r_{ij} between two charged particles is defined as:

$$r_{ij} = \frac{\left\| X_i - X_j \right\|}{\left\| \left(X_i - X_j \right)/2 - X_{best} \right\| + \varepsilon} \tag{7}$$

Where X_i and X_j are the positions of the ith and jth CPs, respectively; X_{best} is the position of the best current CP; and ε is a small positive number to avoid singularities.

Step 2. CP ranking. Evaluate the values of the fitness function for the CPs, compare with each other and sort them in an increasing order.

Step 3. CM creation. Store the number of the first CPs equal to charged memory size (CMS) and their related values of the fitness functions in the charged memory (CM).

Level 2: Search

Step 1. Attracting force determination. Determine the probability of moving each CP toward the others considering the following probability function:

$$P_{ij} = \begin{cases} 1 & \dfrac{fit(i) - fitbest}{fit(j) - fit(i)} > rand \vee fit(j) > fit(i) \\ 0 & otherwise \end{cases} \tag{8}$$

And calculate the attracting force vector for each CP as follows:

$$F_j = q_j \sum_{i, i \neq j} \left(\frac{q_i}{a^3} r_{ij} i_1 + \frac{q_i}{r_{ij}^2} i_2 \right) ar_{ij} P_{ij} \left(X_i - X_j \right)$$

$$\begin{cases} j = 1, 2, .., N \\ i_1 = 1, i_2 = 0 \Leftrightarrow r_{ij} < a \\ i_1 = 0, i_2 = 1 \Leftrightarrow r_{ij} \geq a \end{cases} \tag{9}$$

Where F_j is the resultant force affecting the jth CP and ar_{ij} indicates the kind of force and defined as:

$$ar_{ij} = \begin{cases} +1 & rand < 0.8 \\ -1 & otherwise \end{cases} \tag{10}$$

Step 2. Solution construction. Move each CP to its new position and find its velocity using the following equations:

$$X_{j,new} = rand_{j1} . k_a . \frac{F_j}{m_j} . \Delta t^2 + rand_{j2} . k_v . V_{j,old} . \Delta t + X_{j,old} \tag{11}$$

$$V_{j,new} = \frac{X_{j,new} - X_{j,old}}{\Delta t} \tag{12}$$

Where $rand_{j1}$ and $rand_{j2}$ are two random numbers uniformly distributed in the range (0,1). m_j is the mass of the CPs, which is equal to q_j in this paper. Δt is the time step, and it is set to 1. k_a is the acceleration coefficient; k_v is the velocity coefficient to control the influence of the previous velocity. In this paper k_a and k_v are taken as 0.5.

Step 3. CP position correction. If a CP exits from the allowable search space, its position should be corrected using the HS-based handling approach as described for the HPSACO algorithm [13,14].

Step 4. CP ranking. Evaluate and compare the values of the fitness function for the new CPs; and sort them in an increasing order.

Step 5. CM updating. If some new CP vectors are better than the worst ones in the CM, in terms of their objective function values, include the better vectors in the CM and exclude the worst ones from the CM.

Level 3: Controlling the terminating criterion

Repeat the search level steps until a terminating criterion is fulfilled.

2.2.2. The enhanced charged system search

This algorithm was proposed by Kaveh and Talatahari [6]. In the CSS algorithm, when the calculations of the amount of forces are completed for all CPs, the new locations of agents are determined (step 2). CM updating is also fulfilled after moving all CPs to their new locations. All these conform to discrete time concept. In the optimization problems, this is known as iteration. In other words, the modification of the space-time for the multi-agent algorithms is often performed when an iteration is completed and the new iteration is not started yet. In the ECSS, this assumption of the CSS algorithm is ignored. In the ECSS, time changes continuously and after creating just one solution, all the updating processes are performed. Using this ECSS, the new position of each agent can affect the moving process of the subsequent CPs while in the standard CSS unless an iteration is completed, the new positions are not utilized. This is the main difference between the ECSS and the standard CSS algorithms [7].

2.3. Design of grillage systems

According to LRFD-AISC conditions [11], for designing a grillage system, displacement and strength constraints must be considered as follow:

2.3.1. Maximum displacement constraint

$$\frac{\delta_i}{\delta_i^u} \leq 1 \qquad i = 1, 2, ..., nj \tag{13}$$

Where δ_i is the displacement of joint i and δ_i^u is its upper bound.

2.3.2. The strength constraints without the effect of warping

$$\frac{M_{u,i}}{\phi_b . M_{n,i}} \leq 1 \qquad i = 1, 2, ..., nm \tag{14}$$

$$\frac{V_{u,i}}{\phi_v V_{n,i}} \leq 1 \qquad i = 1, 2, ..., nm \tag{15}$$

Where $M_{u,I}$ is the required flexural strength in member i; $M_{n,I}$ denotes the nominal flexural strength; ϕ_b is flexural resistance reduction factor which is equal to 0.9; $V_{u,I}$ is the factored service load shear for member i; $V_{n,I}$ is the nominal strength in shear; and ϕ_v represents the resistance factor for shear given as 0.9.

According to LRFD-AISC, the nominal flexural strength for a rolled compact section is computed as follow:

$$M_n = \begin{cases} M_p = Z_x F_y \leq 1.5 S_x F_y & \lambda \leq \lambda_p \\ M_p - (M_p - M_r)\dfrac{\lambda - \lambda_r}{\lambda_r - \lambda_p} & \lambda_p < \lambda \leq \lambda_r \\ M_{cr} = S_x F_{cr} \leq M_p & \lambda > \lambda_r \end{cases} \quad (16)$$

Where M_p is the plastic moment; Z_x is the plastic section modulus; S_x is the section modulus; M_{cr} is the buckling moment; F_{cr} is the critical stress and M_r is the limiting buckling moment, given as:

$$M_r = (F_y - F_r)\, S_x \quad (17)$$

Where F_r is the compressive residual stress in the flange, which is given as 69 MPa for rolled shapes in the code.

In the above equation, $\lambda = b_f/(2t_f)$ for I-shaped member flanges, in which b_f and t_f are the width and the thickness of the flange; $\lambda = h/t_w$ for a beam web, in which $h=d-2K$ plus allowance for undersize inside fillet at compression flange for rolled I-shaped sections; d is the depth of the section; k is the distance from the outer face of the flange to the web toe of the fillet; t_w is the web thickness. λ_p and λ_r are given in table LRFD-B5.1 of the code as

$$\lambda_r = \begin{cases} 0.38\sqrt{\dfrac{E}{F_y}} & \textit{for compression flange} \\ 3.76\sqrt{\dfrac{E}{F_y - F_r}} & \textit{for the web} \end{cases} \quad (18)$$

$$\lambda_p = \begin{cases} 0.83\sqrt{\dfrac{E}{F_y - F_r}} & \textit{for compression flange} \\ 5.70\sqrt{\dfrac{E}{F_y}} & \textit{for the web} \end{cases} \quad (19)$$

Where E is the modulus of elasticity and F_y is the yield stress of steel. It is apparent that M_n is computed for the flange and for the web separately by using the corresponding λ values. The nominal moment strength of the section is the smallest of these values.

The nominal shear strength of a rolled compact and non-compact W-section is computed from the data given in LRFD-AISCF2.2 as follows:

$$V_n = \begin{cases} 0.6 F_{yw} A_w & \dfrac{h}{t_w} \leq 2.45\sqrt{\dfrac{E}{F_{yw}}} \\ 1.47 F_{yw} A_w \dfrac{t_w}{h}\sqrt{\dfrac{E}{F_{yw}}} & 2.45\sqrt{\dfrac{E}{F_{yw}}} < \dfrac{h}{t_w} \leq 3.07\sqrt{\dfrac{E}{F_{yw}}} \\ A_w \dfrac{4.52 E t_w^2}{h^2} & 3.07\sqrt{\dfrac{E}{F_{yw}}} < \dfrac{h}{t_w} \leq 260 \end{cases} \quad (20)$$

2.3.3. The strength constraints considering the effect of warping

For a steel grillage system with its members rigidly connected to each other, bending and torsional moments develop at their ends due to external loading and it causes these thin-walled elements warp. If the warping is restrained, it causes large values of normal stresses in the section. Hence, it becomes necessary to consider the effect of warping in the analysis of grillage systems [15, 16, 17].

According to LRFD-AISC [11], we utilize the following strength constraint instead of equation (14), when the effect of warping is included:

$$\pm\frac{\sigma_{bx}}{\phi_b F_{cr}} \pm \frac{\sigma_{by}}{0.9F_y} \pm \frac{\sigma_w}{0.9F_y} \leq 1 \qquad i = 1, 2, \ldots, n \quad (21)$$

In which F_{cr} is the critical flexible stress; σ_b is the normal stress due to bending about either the x-axis or the y-axis and σ_w is the warping normal stress that is computed as follow:

$$\sigma_w = \frac{M_w w}{I_w} \quad (22)$$

Where w is the warping function and I_w is the warping moment of inertia. Other constraints are the same as the grillage system without warping.

Here, direct stiffness method is used to analyze grillage systems. For a grillage system without considering the effect of warping, we can use a 6x6 element stiffness matrix in which there are three degrees of freedom for each node as given in detail in Ref. [18].

If the effect of warping is considered, the rate of twist will be added to the displacement matrix and then the number of degree of freedom will be four. The corresponding matrix is given in details in Ref. [18].

3. Design examples

In this section, the influence of different conditions of a grillage system, i.e. different spacing, boundary conditions and number of elements on the objective function are compared for covering a distinct area (15m×15m) with an evenly distributed load 15 kN/m^2 (the total load is 3375 kN), in order to investigate their effects on the weight and cost of the structure. The warping effect is taken into account for this investigation.

The assumptions used in the examples are as follow: The yield stress of materials is set to 250 MPa. The modulus of elasticity and the shear modulus are taken as 205 kN/mm^2 and 81 kN/mm^2, respectively. The discrete set from which the design algorithm selects the sectional designations for grillage members is considered to be the set of 272 W-sections as given in LRFD-AISC. The maximum vertical displacement for each node is up to 25 mm. The grillage systems are optimized by the CSS and ECSS algorithms. A population of 20 CPs is selected in these algorithms. The maximum number of iterations is assumed to be 250. The values of k_a and k_v is taken as 0.5 and the radius of the particles is chosen equal to unit. Four groups are allocated to longitudinal and transversal beams; group 1 and group 2 are assigned to outer and inner longitudinal beams respectively, while group 3 and group 4 are assigned to outer and inner transversal beams respectively. MATLAB software is used for the analysis and optimization of the aforementioned grillage systems.

Example 1

In this example a grillage system with five bays in each direction is considered to cover a district area and the general model of this grillage is shown in Figure 1. It is assumed that the total external load (3375kN) is exerted to the 16 joints of the grillage system as point loads. Therefore, every node carries a point load of 210.9375kN. This grillage is optimized for two cases (i) in Case 1 all the supports and elements of the grillages are considered and (ii) in Case 2, four supports (1, 4, 29 and 32) and the related elements (1, 4, 37 and 40) are neglected. The results are shown in Table 1 and Table 2 for these two cases, respectively. From Table 1, it can be clearly seen that the warping has a substantial effect on the whole weight of the grillage. In addition, the optimization results obtained using ECSS algorithm for both fixed and hinged supports are better compared to the results using the CSS algorithm. The optimization results using both algorithms also reveal that the total weight of grillage is doubled when a hinged support is used.

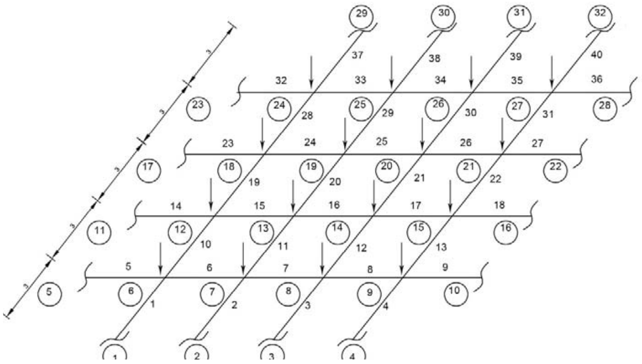

Fig. 1 A general model of 40-member grillage system

The optimization results of the grillage system for Case 2 are summarized in Table 2. Comparing with the results of Case 1 from Table 1, it can be concluded that ignoring a limited number of the supports and the corresponding elements has insignificant effects on the weight of the grillage. The convergence histories of the two algorithms are depicted in Figures 2-5 for both cases considering warping. Based on Figures 2-5 and the results summarized in Tables 1 and 2, one can conclude that ECSS gives better results in

Table 1 Case 1, A regular 40-member grillage system which has 4 supports in each side

Search Method		Standard CSS		Enhanced CSS	
Support Type	Group	Without Warping	With Warping	Without Warping	With Warping
Fixed	Group 1	'W310X38.7'	'W410X53'	'W460X52'	'W610X101'
	Group 2	'W460X89'	'W920X238'	'W610X101'	'W760X196'
	Group 3	'W310X52	'W460X89'	'W150X13.5'	'W150X22.5'
	Group 4	'W840X176'	'W460X113'	'W760X185'	'W360X134'
	Weight (kg)	10446.91	14790	10536.2	13605
	$\Delta_{\max}$ (mm)	-20.16	-12.36	-19.31	-19.46
Maximum Strength Ratio		0.98	0.988	0.977	0.982
Hinged	Group 1	'W250X58'	'W530X101'	'W200X15'	'W250X73'
	Group 2	'W1000X272'	'W840X176'	'W460X158'	'W1100X390'
	Group 3	'W460X82'	'W530X123'	'W460X60'	'W610X101'
	Group 4	'W1100X343'	'W1100X433'	'W1100X499'	'W920X201'
	Weight (kg)	22650	24990	21960	22935
	$\Delta_{\max}$ (mm)	-23.3	-23.57	-24.2	-24.64
Maximum Strength Ratio		0.547	0.886	0.896	0.987

Table 2 Case 2, A 36-member grillage system by removing 4 supports and related elements in Fig. 1

Search Method		Standard CSS		Enhanced CSS	
Support Type	Group	Without Warping	With Warping	Without Warping	With Warping
Fixed	Group 1	'W530X72'	'W530X109'	'W460X60'	'W610X101'
	Group 2	'W760X173'	'W460X144'	'W530X66'	'W920X201'
	Group 3	'W200X22.5'	'W310X107'	'W150X24'	'W530X72'
	Group 4	'W610X101'	'W920X201'	'W920X201'	'W460X128'
	Weight (kg)	10759.43	15546	10242	14196
	$\Delta_{\max}$ (mm)	-20.20	-14.23	-16.06	-14.35
Maximum Strength Ratio		0.987	0.987	0.974	0.973
Hinged	Group 1	'W410X60'	'W610X113'	'W460X60'	'W530X123'
	Group 2	'W1100X390'	'W1100X433'	'W530X82'	'W1100X390'
	Group 3	W150X13'	'W150X22.5'	'W150X13'	'W150X24'
	Group 4	'W1000X272'	'W690X217'	'W1100X499'	'W840X226'
	Weight (kg)	21880.47	23295	19425	22602
	$\Delta_{\max}$ (mm)	-22.9	-24.04	-24.77	-24.42
Maximum Strength Ratio		0.97	0.75	0.928	0.96

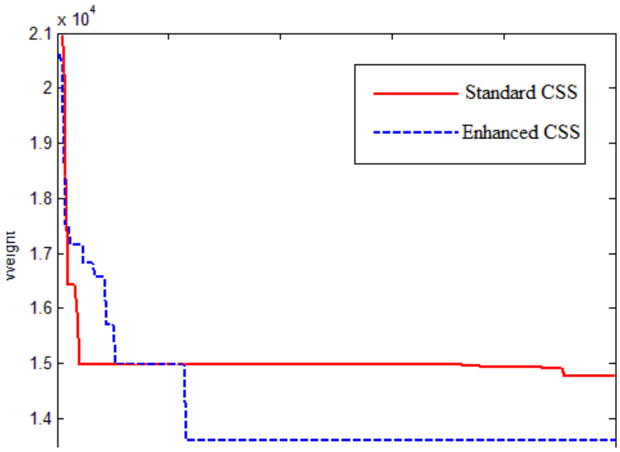

Fig. 2 Convergence curve of the 40-member grillage system considering warping and fixed supports

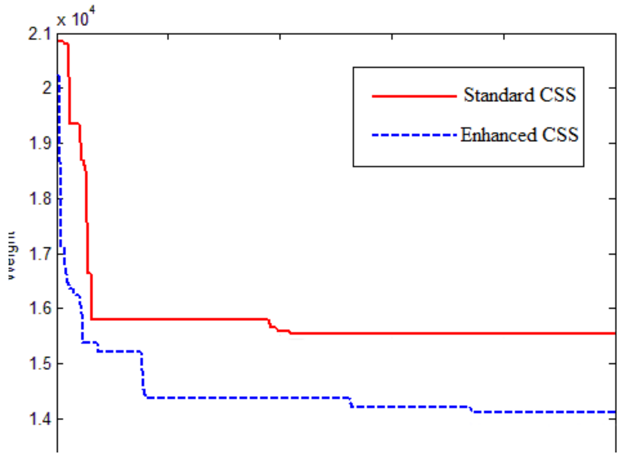

Fig. 4 Convergence curve of the 36-member grillage system considering warping and fixed supports

fixed supports

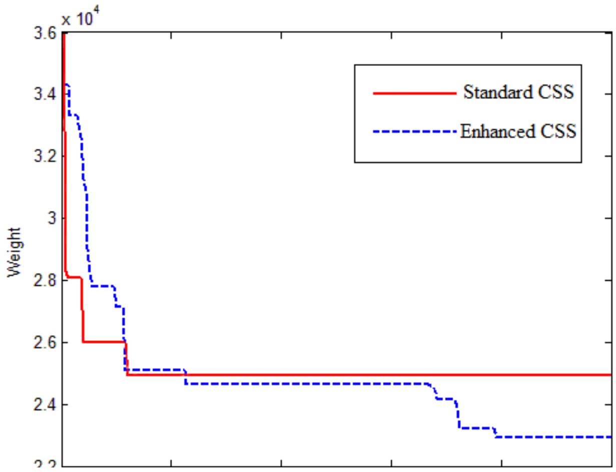

Fig. 3 Convergence curve of the 40-member grillage system considering warping and hinged supports

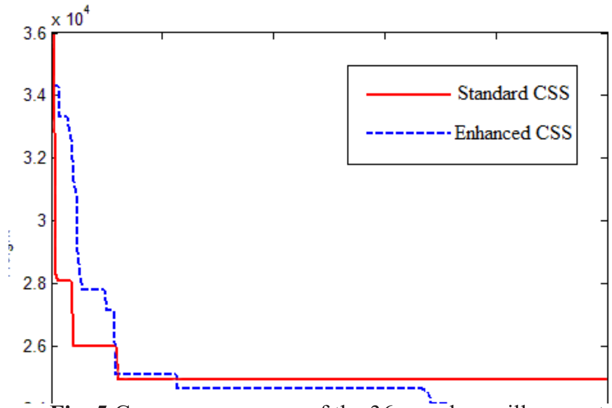

Fig. 5 Convergence curve of the 36-member grillage system considering warping and hinged supports

comparison to the CSS algorithm, e.g. the weight of a 36-member grillage system with fixed supports without considering warping is 10242 kg which is 4.8% lighter than the result of the CSS.

Example 2

A 50-member grillage system is considered in this example as depicted in Figure 6. As can be seen from the is figure, the upper and lower supports in Figure 1 are replaced by beams of 15 m length with two supports at their ends, thus the number of supports reduced to 12 while the number of beam elements increased to 50. The number of free nodes is 24; hence a concentrated load of 140.625kN is applied on each free node. The effect of beam spacing on the weight of grillage structure is also investigated in this example. Similar to Example 1, the optimization is performed for two cases as shown in Table 3 and Table 4, respectively.

According to the results obtained, there is a considerable

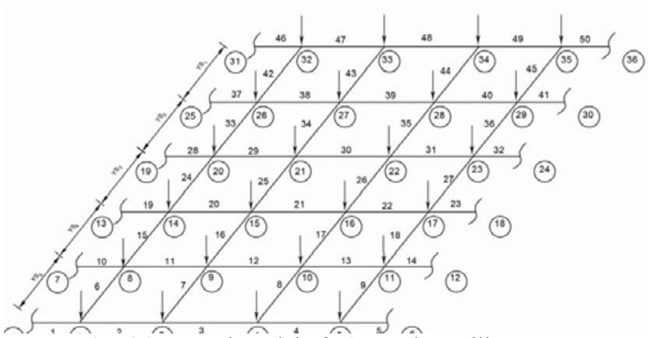

Fig. 6 A general model of 50-member grillage system

increase in the weight of the grillage for both types of supports and an increase in the maximum displacement for fixed supports if there is no possibility to place supports

Table 3 Case 1, A regular 50-member grillage system with end bearings in 2 sides of it

Search Method		Standard CSS		Enhanced CSS	
Support Type	Group	Without Warping	With Warping	Without Warping	With Warping
Fixed	Group 1	'W610X140'	'W610X125'	'W610X140'	'W530X165'
	Group 2	'W760X134'	'W690X140'	'W690X125'	'W610X153'
	Group 3	'W200X26.6'	'W310X67'	W360X44'	'W150X29.8'
	Group 4	'W360X32.9'	'W530X72'	'W200X22.5'	'W250X38.5'
	Weight (kg)	14025	16320	13695	16179
	Δ_{max} (mm)	-24.3	-22.85	-24.74	-24.85
Maximum Strength Ratio		0.885	0.258	0.943	0.271
Hinged	Group 1	'W1000X314'	'W1000X272'	'W1000X321'	'W840X329'
	Group 2	'W1000X296'	'W1100X343'	'W1000X314'	'W1000X321'
	Group 3	'W150X37.1'	'W310X107'	'W200X22.5'	'W150X24'
	Group 4	'W200X26.6'	'W360X110'	'W130X23.8'	'W610X155'
	Weight (kg)	29091	35250	29859	34500
	Δ_{max} (mm)	-22.43	-23.58	-21.56	-24.13
Maximum Strength Ratio		0.396	0.12	0.38	0.12

Table 4 Case 2, An irregular 50-member grillage system with different beam spacing

Search Method		Standard CSS		Enhanced CSS	
Support Type	Group	Without Warping	With Warping	Without Warping	With Warping
Fixed	Group 1	'W610X113'	'W760X173'	'W610X125'	'W760X161'
	Group 2	'W610X113'	'W610X140'	'W610X113'	'W690X125'
	Group 3	'W200X19.3'	'W360X44'	W100X19.3'	'W310X32.7'
	Group 4	'W100X19.3'	'W410X38.8'	'W250X22.3'	'W460X82'
	Weight (kg)	11328	16074	11778	15771
	Δ_{max} (mm)	-24.009	-19.36	-24.11	-18.1
Maximum Strength Ratio		0.994	0.264	0.997	0.267
Hinged	Group 1	'W920X271'	'W920X420'	'W1000X249'	'W1000X350'
	Group 2	'W920X271'	'W920X271'	'W1000X249'	'W920X271'
	Group 3	'W360X32.9'	'W250X28.4'	'W200X59'	'W250X44.8'
	Group 4	'W150X24'	'W150X13'	'W250X38.5'	'W200X35.9'
	Weight (kg)	26097	30102	25335	29181
	Δ_{max} (mm)	-24.35	-24.57	-23.7	-24.78
Maximum Strength Ratio		0.397	0.35	0.411	0.134

in 4 sides of the grillage. This increment can obviously be seen by comparing the results provided in Table 1 and Table 3.

In Case 1, the values of XS_1, XS_2, XS_3, XS_4, XS_5, YS_1, YS_2, YS_3, YS_4 and YS_5 are taken as 3 m in Figure 6. The optimization results for the hinged support in Table 3, compared to the results in Table 1, indicate an increase of about 30 to 50 % in the grillage weight. The warping has also influence on the weight of the grillage, increasing the weight about 5000 kg.

The results of Case 2, shown in Table 4, indicate that the beam spacing has significant effect on the total weight of the grillage. Case 2 indicates that the beam spacing is increased by expanding their space with the supports. In this case, the beam spacing YS_1, YS_2, YS_3, YS_4 and YS_5 are the same as before and XS_1, XS_2, XS_3, XS_4 and XS_5 are selected as 2m, 3.5m, 4m, 3.5m and 2m, respectively. This indeed resulted in a sharp reduction in the weight of the grillage. For instance, the calculated grillage weight 13695 kg can be decreased to 11778 kg with a small change in the beam spacing. Comparing the results from Table 3 and Table 4 for the hinged supports, it can be concluded that the weight of the grillage in Case 2 is reduced to by nearly 15 %. Morover, it can be concluded that in most of the cases, the ECSS algorithm performs better optimization than CSS.

Figures 7-10 show the convergence history of the two algorithms for the 50-member grillage system in both cases considering warping.

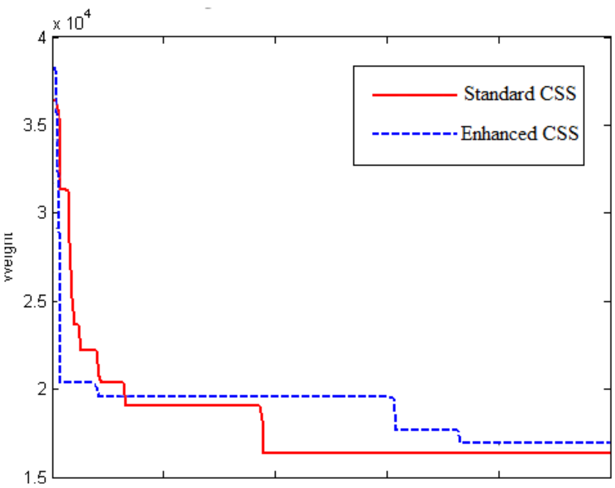

Fig. 7 Convergence curve of the 50-member grillage system considering warping and fixed supports

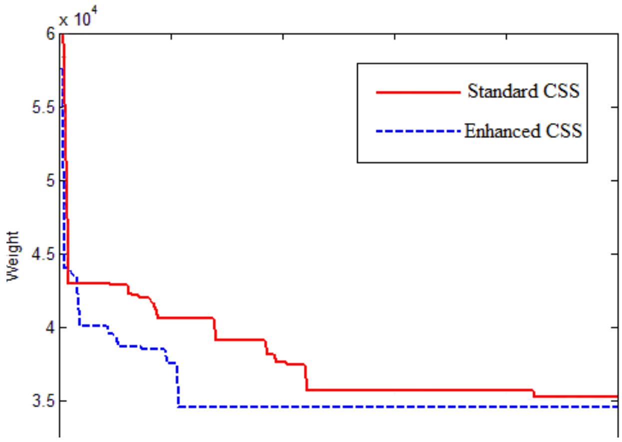

Fig. 8 Convergence curve of the 50-member grillage system considering warping and hinged supports

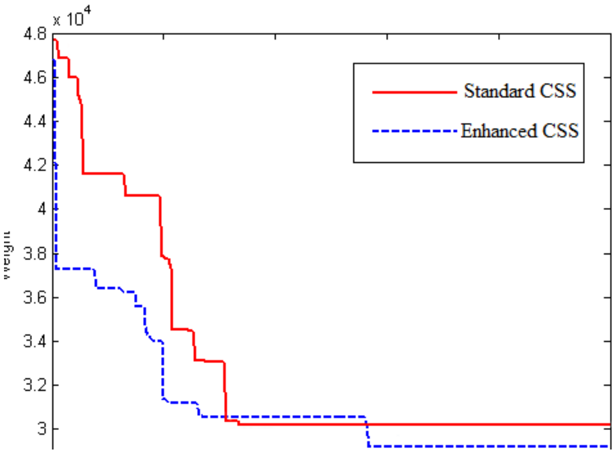

Fig. 10 Convergence curve of the 50-member grillage system considering warping, hinged supports and different spacing

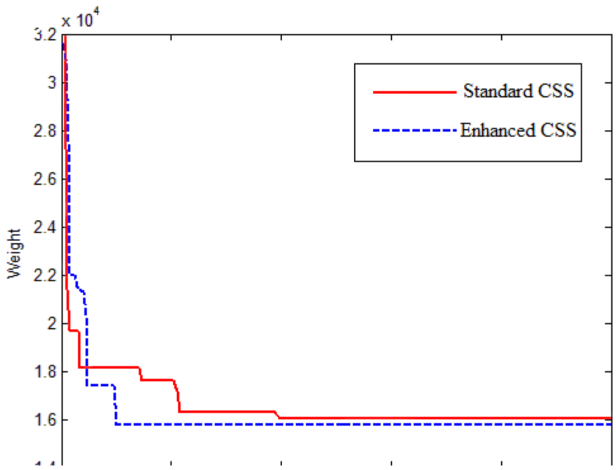

Fig. 9 Convergence curve for the 50-member grillage system considering warping, fixed supports and different spacing

Example 3

In this example, to investigate the effect of beam spacing on weight and maximum displacement of the grillage structure, the beam spacing in the transversal direction is reduced to the half of the distance and also in longitudinal direction, the number of bays is increased from 5 to 6 so that the number of grillage elements is raised to 104, Figure 11. Similar to the previous examples, the distributed load is assumed to be fixed with 15kN/m2. Since the area of the grillage is constant, subsequently a point load of 75kN is applied on each node. Figure 11 illustrates a 104-member grillage system which is optimized for two cases in this example and the optimization results are provided in Tables 5 and 6.

In Case 1 of this example, the changes in the weight of grillage were negligible compared to Case 1 of example 1. Considering groups 1-4 in Table 5, it can be concluded that the cross-sections which are selected for group 4 (inner transversal beams) have large depth while the selected cross-sections for

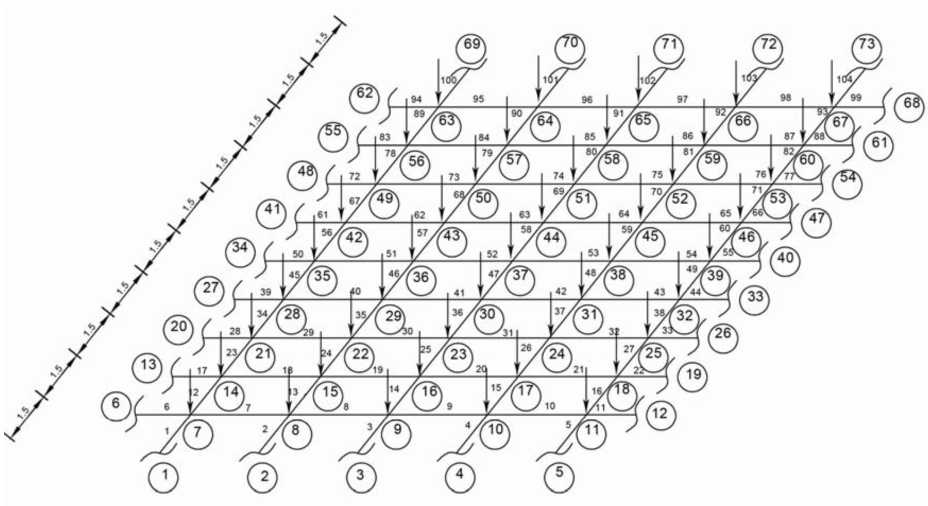

Fig. 11 A general model of 104-member grillage system

Table 5 A 104-member grillage with decreasing beam spacing in one direction

Search Method		Standard CSS		Enhanced CSS	
Support Type	Group	Without Warping	With Warping	Without Warping	With Warping
Fixed	Group 1	'W200X46.1'	'W200X26.6'	'W200X15'	'W150X29.8'
	Group 2	'W250X38.5'	'W310X38.7'	'W360X32.9'	'W310X38.7'
	Group 3	W310X21'	W250X25.3'	'W150X13'	'W250X25.3'
	Group 4	'W760X134'	'W760X196'	'W760X147'	'W840X176'
	Weight (kg)	12085.5	14440.5	10909.5	13636.5
	$\Delta_{\max}$ (mm)	-23.4344	-14.6	-21.18	-14.24
Maximum Strength Ratio		0.95	0.89	0.977	0.9
Hinged	Group 1	'W310X21'	'W530X82'	'W250X25.3'	'W200X41.7'
	Group 2	'W310X28.3'	'W200X46.1'	W250X28.4'	W250X49.1'
	Group 3	'W150X13'	'W360X57.8'	'W150X29.8'	W360X32.9'
	Group 4	'W1100X390'	'W1000X371'	'W1100X343'	'W1100X390'
	Weight (kg)	21541.5	25729.5	20070	24943.5
	$\Delta_{\max}$ (mm)	-21.21	-24.96	-24.87	-20.58
Maximum Strength Ratio		0.866	0.915	0.95	0.86

Table 6 Optimization results of a 100-member grillage system by eliminating 4 elements in Figure 11

Search Method		Standard CSS		Enhanced CSS	
Support Type	Group	Without Warping	With Warping	Without Warping	With Warping
Fixed	Group 1	'W200X22.5'	'W150X13'	'W250X22.3'	'W250X32.7'
	Group 2	'W250X38.5'	'W360X44'	'W200X41.7'	'W360X44'
	Group 3	'W150X13'	'W360X39'	'W150X13.5'	'W150X22.5'
	Group 4	'W690X152'	'W840X176'	'W760X134'	'W760X173'
	Weight (kg)	11485.5	13572	10982.1	13533
	$\Delta_{\max}$ (mm)	-23.12	-15.97	-23	-17
Maximum Strength Ratio		0.995	0.89	0.993	0.96
Hinged	Group 1	'W310X21'	'W360X39'	'W250X17.9'	'W360X32.9'
	Group 2	'W360X32.9'	'W250X58'	'W410X38.8'	'W200X52'
	Group 3	'W460X52'	'W360X44'	'W310X28.3'	'W200X41.7'
	Group 4	'W1100X343'	'W1100X390'	'W1100X343'	'W1100X390'
	Weight (kg)	20684.7	25434	20429.4	24624
	$\Delta_{\max}$ (mm)	-23.31	-22.95	-22.49	-24.17
Maximum Strength Ratio		0.923	0.79	0.923	0.88

group 2 (internal vertical beams) have smaller depth. As a result, it can be concluded that a grillage with a smaller thickness can be achieved by reducing the beam spacing in both directions. But the previous studies showed that reduction in beam spacing in both horizontal and vertical directions results in increase in the weight of the grillage.

The opening in the grillage system, when it is necessary, can be achieved by two methods: (i) changing beam spacing equal to dimensions of the opening which will result in considerable changes in the weight of the grillage, and (ii) removing some elements to reach to a desirable size. Table 6 summarizes the optimization results for the investigation of the opening in the grillage system with 4 openings (3m×3m) (Figure 11). For this purpose, the elements 18, 21, 84 and 87 are removed. As can be seen from the results, there are negligible changes in the weight of the grillage using the second method.

Figures 12-15 show the convergence history of the two algorithms for the 104-member grillage system in both cases considering warping.

Example 4

Figure 16 shows the external loading and the dimensions of a 14-member cantilever grillage system which is optimized by the CSS and ECSS algorithms. Two different groups are employed for designing this grillage system. Group 1 and Group 2 are assigned to the longitudinal and transversal beams, respectively. The maximum vertical displacement for each node is up to 20 mm, for nodes 3, 6, 9 and 12 the vertical displacements are provided in Table 7.

Figure 17 is the convergence history of the two algorithms for the last example. As it can be seen, both CSS and ECSS algorithms lead to optimum designs in less than 40 iterations.

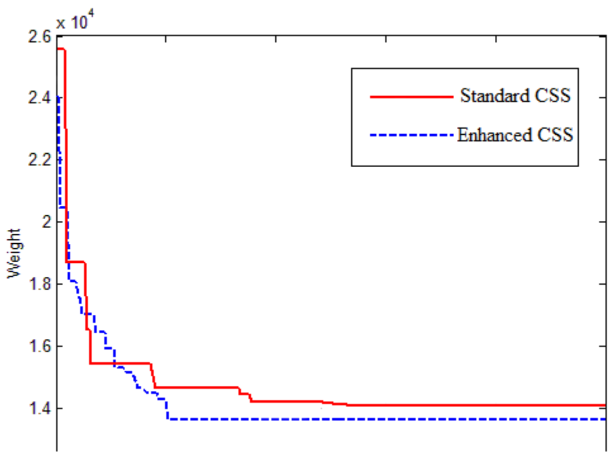

Fig. 12 Convergence curve for the 104-member grillage system considering warping and fixed supports

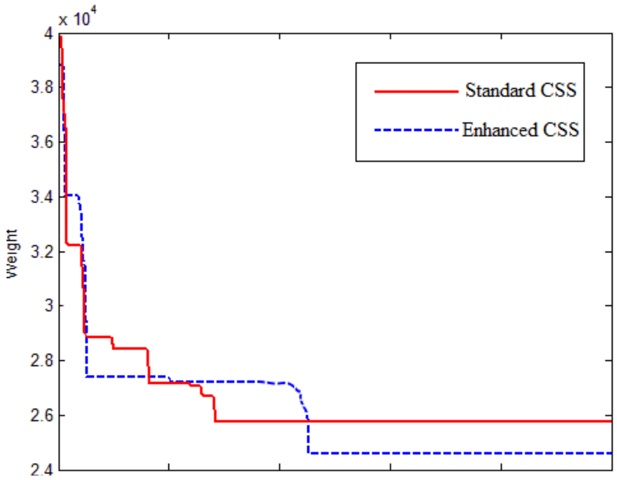

Fig. 13 Convergence curve for the 104-member grillage system considering warping and hinged supports

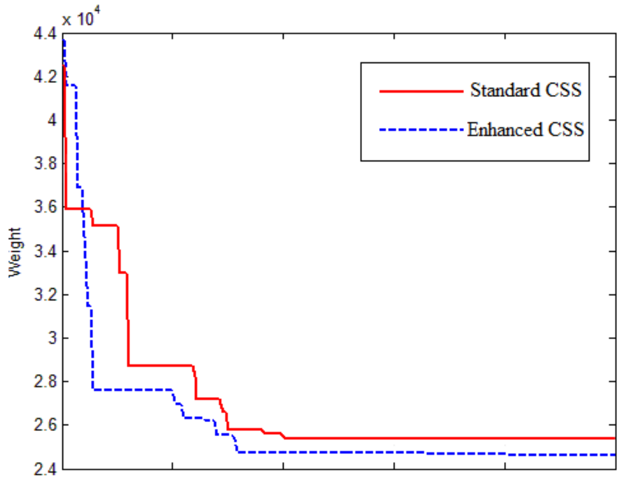

Fig. 15 Convergence curve for the 100-member grillage system considering warping and hinged supports

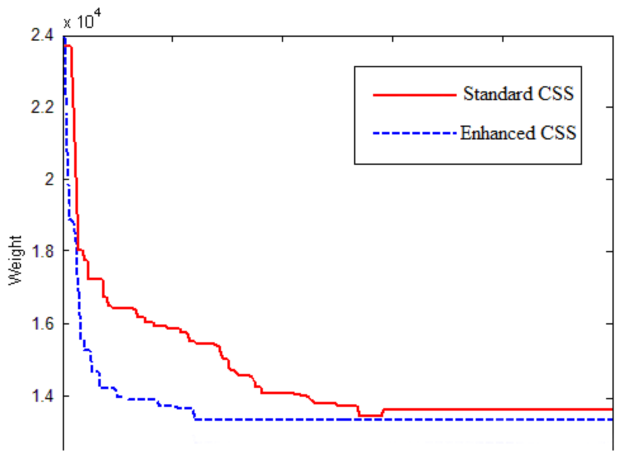

Fig. 14 Convergence curve for 100-member grillage system considering warping and fixed supports

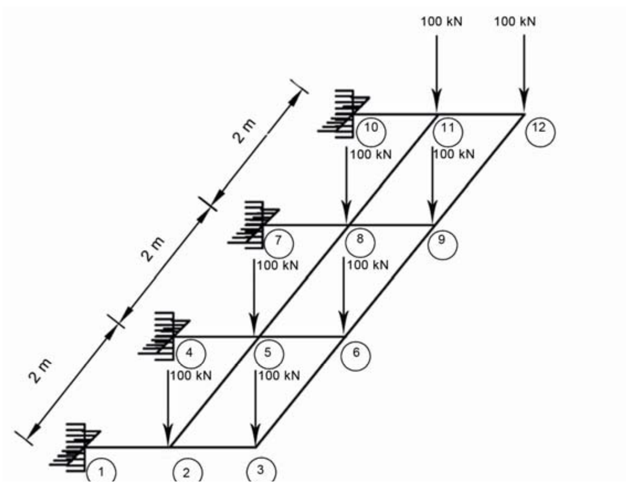

Fig. 16 A 14-member cantilever grillage system

4. Conclusions

In this paper, the optimization of grillages with different boundary conditions and beam spacing is performed using the CSS and ECSS algorithms. The results show that the ECSS algorithm presents a better solution for the optimization of grillages compared to the CSS. Moreover, we studied the effects of warping on the weight of irregular grillage systems. It is found that when the warping is neglected, the optimum design will not be realistic and the weight of grillage will be reduced. The results indicate that the use of hinged supports in grillages instead of fixed supports nearly doubles the weight of the grillage.

The results of optimizing a 14-members cantilever grillage utilizing the CSS and ECSS indicate that the CSS algorithms are highly capable of finding optimal designs with a high convergence rate.

Apparently, replacing supports of the two opposite sides of the grillage by longitudinal beams with two supports at their

Table 7 Comparison of optimum design results of different search method for a 14-member cantilever grillage

Search Method	CPSO	IPSO	Standard CSS	Enhanced CSS
Group 1	'W530X74'	'W460X74'	'W530X72'	'W530X72'
Group 2	'W200X15'	'W150X13.5'	'W150X13.5'	'W150X13'
Weight (kg)	890.58	872.23	853.2	847.2
$\Delta_{\max}$ (mm)	-7.19	-8.86	-7.39	-7.39
Maximum Strength Ratio	0.89	0.964	0.914	0.914

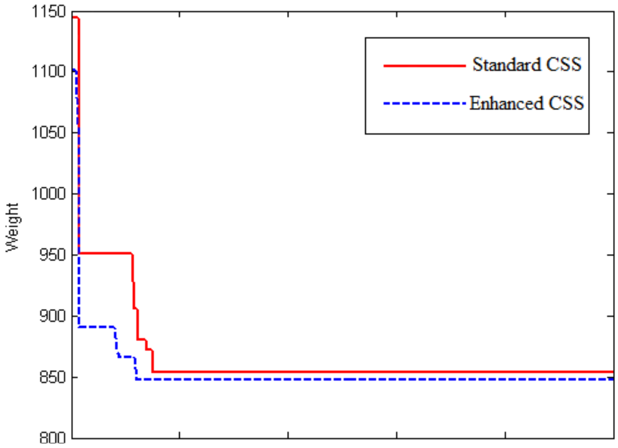

Fig. 17 Convergence curve for the 14-member cantilever grillage system

ends, increases the weight of structure. It is also found that by small changes in the beam spacing, the weight of grillage system reduces significantly.

Furthermore, we investigated the effects of decreasing beam spacing in one direction, increasing numbers of elements, and finally their effects on grillage, in the presence and absence of opening. We found that instead of changing beam spacing to obtain a specified opening, we can achieve better results by removing a number of elements.

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