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Optimum design of composite frames with semi-rigid connections using genetic algorithm

Thiết kế tối ưu kết cấu khung composite với liên kết nửa cứng sử dụng thuật giải di truyền

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ABSTRACT

The purpose of this work presents the behavior of semi-rigid connections in composite structures. A Genetic Algorithm based optimum design method is presented for composite frames with semi-rigid connections. The design algorithm obtains a frame with the least weight (beam, column and number of shear connectors per beam) by selecting appropriate sections from a standard set of AISC.

Keywords: Optimization; genetic algorithms; Composite-frames; semi-rigid connections.

TÓM TẮT

Mục đích bài báo nhằm giới thiệu đến sự ảnh hưởng của liên kết nửa cứng trong kết cấu Composite. Phương pháp tối ưu hóa kết cấu khung Composite với liên kết nửa cứng bằng thuật giải di truyền nhằm tìm ra được kết cấu khung có trọng lượng nhỏ nhất (bao gồm: Dầm, Cột và số lượng các chốt liên kết trên dầm) trên cơ sở các tiết diện từ AISC.

Từ khoá: Tối ưu hóa ; thuật giải di truyền; khung Composite; liên kết nửa cứng.

1. INTRODUCTION

The design of composite frames is more complexity than steel frames because of associated between the concrete slab and the steel beam. The stiffness of a beam will be changed by the variation of shear connectors, affecting the capacity of the frame. Furthermore, conventional analysis and design of composite frames are usually carried out under the assumption that beam to column connections are either fully rigid or ideally pinned. The rigid joint assumption implies that full slope continuity exists between the adjoining members, and that the full gravity moment is transferred from the beam to the column. On the other hand, the assumption of ideally pinned connections implies that the beams will behave as simply supported members and that the columns will carry no gravity moments from the beams. However, most connections in practice are "semi-rigid" and their behavior lies between two extreme cases.

Much work has been done in the optimum design of steel frames or composite frames with the assumption that connections are either fully rigid or ideally pinned (Charles Camp, Jifei Li, Manolis Papadrakakis, ect) [1] using a Genetic Algorithm.

In this study, a Genetic Algorithm based optimum design method is developed for composite frames with semi-rigid beam-to-column connections. The design algorithm obtains the frame with the least weight by selecting appropriate sections for the beams and the columns of the frame from a standard set of available sections of AISC. The serviceable and combined strength constraints are implemented in the design algorithm as they are described in AISC-LRFD.

2. CLASSIFICATION OF BEAM-TO-COLUMN JOINTS

A beam-to-column joint may be classified as rigid, nominally pinned or semi-rigid according to its stiffness, by determining its initial rotational stiffness Rj,ini and comparing this with classification boundaries. As shown in Figure 1, the classification given by prEN 1993-1-1 [4] compares stiffness of the joint with that of the connected member. The purpose is to indicate whether account has to be taken of the influence of joint flexibility on the frame response. The classification boundaries were determined from consideration of ultimate limit states.

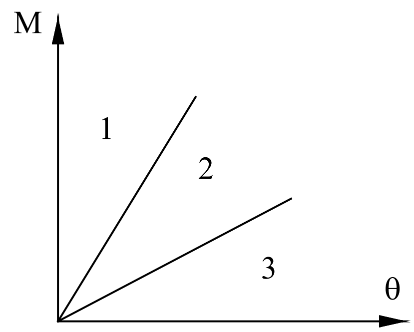

Figure 1. Boundaries for stiffness classification of beam-to-column joints

Zone 1: rigid, if $R_{j,ini} \geq 8\frac{EI_b}{L_b}$

Zone 2: semi-rigid, all joints in zone 2 should be classified as semi-rigid. More accurately, joints in zones 1 or 3 may also be treated as semi-rigid.

Zone 3: nominally pinned, if $Rj,ini \leq 0,5\frac{EI_b}{L_b}$

Where: $E I_b$ is the uncracked flexural stiffness for a cross-section of a composite beam.

L_b is the span of a beam (centre-to-centre of columns).

The relationship between M and θ can be shown by the use of a $M-\theta$ diagram. Various types models have been developed as described by Chen and Lui [10].

In this paper, the Kishi and Chen power model [10] is used for modeling the connection behavior in analysis and design.

3. ANALYSIS OF COMPOSITE FRAMES WITH SEMI-RIGID CONNECTIONS

3.1. The geometrical properties for analysis

The mechanical and geometrical properties of the composite section are required for the calculation of service stresses and deformations. At service stress levels, the concrete in compression and the steel are assumed to behave in a linearly elastic fashion. The uncracked flexural stiffness is , concrete in tension may be considered uncracked, and the flexural stiffness of the cracked section is , the strength of concrete in tension is ignored. [8]

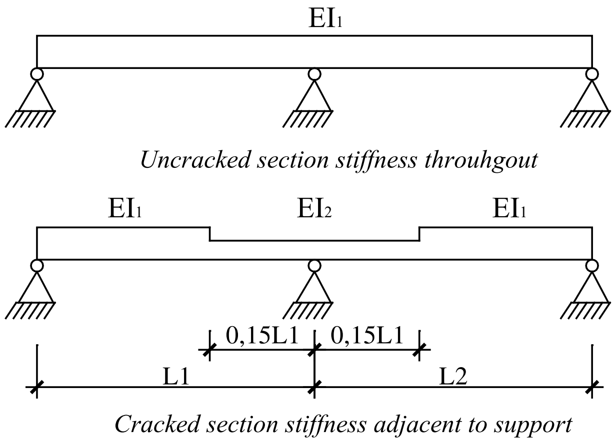

Figure 2. Member stiffnesses

EI_1 is the uncracked section stiffness.

EI_2 is the cracked section stiffness, where:

E is the elastic modulus for structural steel (E_a).

I_1 is the moment of inertia of effective equivalent steel section, calculations are based on the assumption that the concrete in tension is uncracked, and may be taken as being reinforced or unreinforced.

I_2 is the moment of inertia of the effective equivalent steel section. The area of concrete in tension is neglected, but account is taken of steel reinforcement.

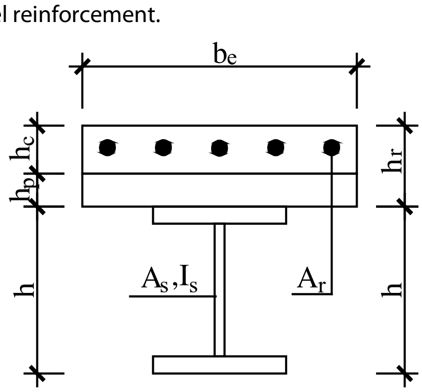

Figure 3. Composite steel-concrete section

The moment of inertia I_1, I_2 can be determined as follows:

$$I_1 = I_s + \frac{b_e h_c^3}{12n} + \frac{A_s b_e h_c (h + h_c + 2h_p)^2}{4(A_s n + b_e h_c)} \quad (1)..$$

$$I_2 = I_s + \frac{A_s A_r (h + 2h_r)^2}{4(A_s + A_r)} \quad (2)$$

In which $n = E_a/E_c$ is the modular ratio, with E_a is the elastic modulus of structural steel, and E_c is that of concrete.

b_e is the effective flange widths given in references [8].

3.2. Analysis of semi-rigid frames

Consider a beam element subjected to the member end forces r_i , i = 1 to 6 and the member end displacement d_i , i = 1 to 6 and Δ is the relative joint translation of the member.

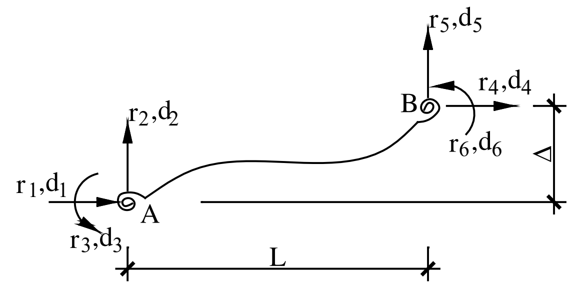

Figure 4. Beam element with connections

The connection are modeled as rotation springs and their initial stiffness of the connections A and B are R_{kiA} and R_{kiB}.

The stiffness matrix of a beam, with rotational springs at the ends is shown by the following matrix [10]:

$$k_{beam} = \frac{EI}{L}\begin{bmatrix} \frac{A}{I} & 0 & 0 & -\frac{A}{I} & 0 & 0 \\ & \frac{(s_{ii}^* + 2s_{ij}^* + s_{jj}^*)}{L^2} & \frac{s_{ii}^* + s_{ij}^*}{L} & 0 & -\frac{(s_{ii}^* + 2s_{ij}^* + s_{jj}^*)}{L^2} & \frac{s_{ij}^* + s_{jj}^*}{L} \\ & & s_{ii}^* & 0 & \frac{-(s_{ii}^* + s_{ij}^*)}{L} & s_{ij}^* \\ & & & \frac{A}{I} & 0 & 0 \\ & & & & \frac{(s_{ii}^* + 2s_{ij}^* + s_{jj}^*)}{L^2} & -\frac{(s_{ij}^* + s_{jj}^*)}{L} \\ & & & & & s_{jj}^* \end{bmatrix} \quad (3)$$

$$\text{Where } s_{ii}^* = (4 + \frac{12EI}{LR_{kiB}})/R^* \quad (4)$$

$$s_{ii}^* = (4 + \frac{12EI}{LR_{kiB}})/R^* \quad (5)$$

$$s_{ij}^* = s_{ji}^* = 2/R^* \quad (6)$$

In which:

$$R^* = \left(1 + \frac{4EI}{LR_{kiA}}\right)\left(1 + \frac{4EI}{LR_{kiB}}\right) - \left(\frac{EI}{L}\right)^2 \frac{4}{R_{kiA}R_{kiB}} \quad (7)$$

For column, the stiffness matrix, takes the usual form:

$$k_{col} = \frac{EI}{L}\begin{bmatrix} \frac{12}{L^2}\varphi_1 & 0 & \frac{6}{L}\varphi_2 & -\frac{12}{L^2}\varphi_1 & 0 & \frac{6}{L}\varphi_2 \\ & \frac{A}{I} & 0 & 0 & -\frac{A}{I} & 0 \\ & & 4\varphi_3 & -\frac{6}{L}\varphi_3 & 0 & 2\varphi_4 \\ & & & \frac{12}{L^2}\varphi_1 & 0 & -\frac{6}{L}\varphi_2 \\ & & & & \frac{A}{I} & 0 \\ & & & & & 4\varphi_3 \end{bmatrix} \quad (8)$$

Where $\varphi_1, \varphi_2, \varphi_3$ and φ_4 are the stability functions given in references [10].

The beam stiffness matrix and the column stiffness matrix can be assembled to form the structure stiffness matrix K for a given structure.

4. GENETIC ALGORITHM

The optimization technique that has received considerable attention in the past few decades is Genetic Algorithm (GA). Originated by Holland (1975) [7], GA is a search strategy based on the rules of natural genetic evolution. GAs randomly create an initial set of possible solutions, each of which is represented as an equivalent string of genes or chromosomes that will be later combined with genes from other individual strings. As in a biological system subjected to external constraints, the fittest members of the initial population are given better chances of reproducing and transmitting parts of their genetic heritage to the next generation. It is expected that some members of the new population will acquire the best characteristics of both parents and, being better adapted to the environmental conditions, will provide an improved solution to the problem. The process is repeated many times, until all members of a given generation share the same genetic heritage (or the processing time is over). The members of these final generations, who are often quite different from their ancestors, possess genetic information that corresponds to the best solution to the optimization problem.

The basic operators of GAs include: reproduction, crossover, and mutation. The reproduction operation simulates the survival of the fittest strategy in a GA. The crossover operation creates variations in the solution population by producing new solutions that consist of parts taken from selected parent solutions. The mutation operation introduces the possibility of random changes in the solution population.

4.1. Objective function

For the optimization problem, the total cost is minimized by the objective function. The total costs of a composite frame is the sum of steel beam and column costs and the shear connector costs. The objective function can be expressed as follows Bhatti (1996) [11]:

$$F(x) = \sum_{i=1}^{n+m} W_{si} L_i + \sum_{j=1}^{n} N_{sj} C_{sm} \qquad (9)$$

Where:

F(x) is the objective function.

n is the total number of beams.

m is the total number of columns.

W_s is the weight of steel.

L is the length of a member.

N_s is the total number of connectors per beam.

C_{sm} is the transformed weight of one stud.

4.2. LRFD design constraints

Composite beam have four constraints [1]. These constraints are for sagging and hogging moment, vertical displacement and height of beam. The beam constraints may be expressed as:

$$g_i = \begin{cases} 0 & \text{if} \quad m_i \le 0 \\ m_i & \text{if} \quad m_i > 0 \end{cases} \qquad (10)$$

Where m_i is the degree of violation of constraint g_i.

The shear connectors have two constraints. In general, the connector constraints may be expressed as:

$$s_i = \begin{cases} 0 & \text{if} \quad q_i \le 0 \\ q_i & \text{if} \quad q_i > 0 \end{cases} \qquad (11)$$

Where q_i is the degree of violation of constraint s_i.

Composite column have four constraints. These constraints enforce LRFD requirements on beam-column interaction, shape compactness (for local stability), and frame stability. The column constraints may be expressed as:

$$c_i = \begin{cases} 0 & \text{if} \quad n_i \le 0 \\ n_i & \text{if} \quad n_i > 0 \end{cases} \qquad (12)$$

Where n_i is the degree of violation of constraint c_i.

There are several penalty function schemes proposed for structural optimization design (Camp, 1998) [1]. The quadratic penalty function used in this study for composite frames is:

$$\Phi = \prod_{i=1}^{4}(1+g_i)^2 . \prod_{j=1}^{4}(1+c_j)^2 . \prod_{k=1}^{2}(1+s_k)^2 \qquad (13)$$

Having computed a penalty factor, the fitness value of particular solution string is obtained by multiplying the objective function (structural weight) by the corresponding penalty factors:

$$F = W \prod_{i=1}^{n} \Phi_i \qquad (14)$$

Where F is the string fitness (penalized objective function);

n is the total number of points where the constraints are checked;

W is the weight (volume) of the entire structure (objective function).

4.3. Algorithm

The optimum design for composite frame based on Genetic Algorithm consists of the following steps:

1/ Initialize the population size, the maximum number of generations, the current generation number and the current generation count used to test for convergence.

2/ Create the initial population at random where each individual frame is selected by AISC module (AISC Design Manual.AISC1993) [12].

3/ Analyze and calculate the weight, internal force, displacement, and so on of each individual in the initial population via a OBJFUNCTION module. Evaluate all individuals in the population and compute the constraint violations.

4/ Calculate the Fit value for each individual in the initial population is based on the penalty function.

5/ Select the individual in the population based on individual fit values.

6/ Reproduce population by which using the operators of CROSSOVER and MUTATION.

+ CROSSOVER: The crossover operation exchanges the genetic material of two parent individuals to create an offspring

+ MUTATION: In order to explore outlying area of the design space. The mutation creates diversity in the population by randomly introducing new genetic material.

Although, there are no established standards or rules-of-thumb defining crossover and mutation rates, it is common in binary Genetic Algorithms to use higher crossover rates (0.50 to 0.70) and lower mutation rates (0.01 to 0.10). It is suggested that the need for higher mutation rate when object representations of the design variables are used.

7/ Assign the new individuals in to the current population, and repeat the analysis and calculation in step 3.

8/ Evaluate all individuals in the new population.

9/ Repeat the steps from 5 to 8 until the convergence satisfied.

5. DESIGN EXAMPLE

The three-storey, two-bay composite frame is considered to optimum design semi-rigid connections. Two different types of semi-rigid connections are considered in this example are: "Top and Seat Angles without Double Web" and "Top and Seat Angles with Double Web Angle". Figure 4 shows the frame configuration, dimensions, loading, and numbering of joints and grouping of members. Material properties are: F_y = 36 ksi, f'_c = 3 ksi, E_s = 29000ksi, =145 lb/m^3 , the beam spacing is 10 feet and the depth of concrete slab is 4.5 inch.

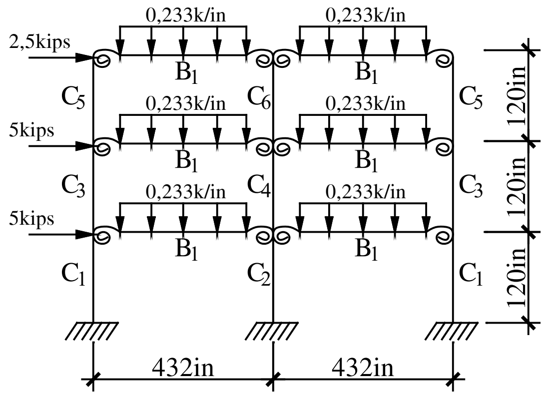

Figure 5. Three-storey, two-bay composite frame

Genetic Algorithm is a method that has random characteristic. In order to find the good result, the program should be run several times (5-10 times). However, besides algorithm should be run several times to ensure to obtain good result, Genetic Algorithm has to be selected a suitable model. That means parameters of GA should be selected appropriately (population size, probability of crossover and probability of mutation). If we select an unsuitable model, the solution should be converged soon. Data and the search will be stopped in the short period. This may not make a good result. So, we should check whether the method is good or not by study of the parameters of Genetic Algorithm.

Study values of objective function based on population size

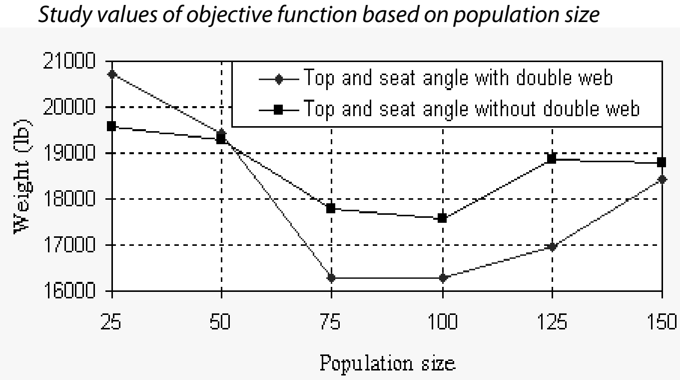

Figure 6. Study based on Population size

Study values of objective function based on probability of crossover

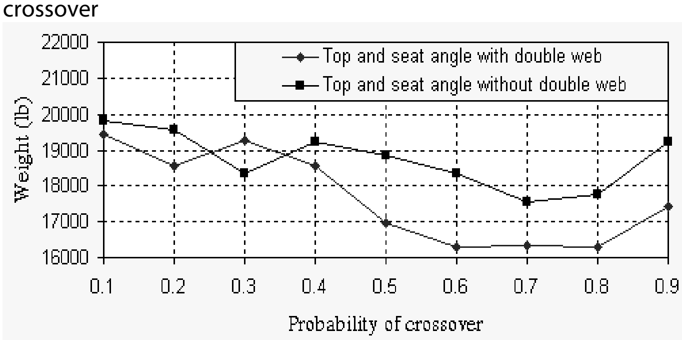

Figure 7. Study based on Probability of crossover

Study values of objective function based on probability of mutation

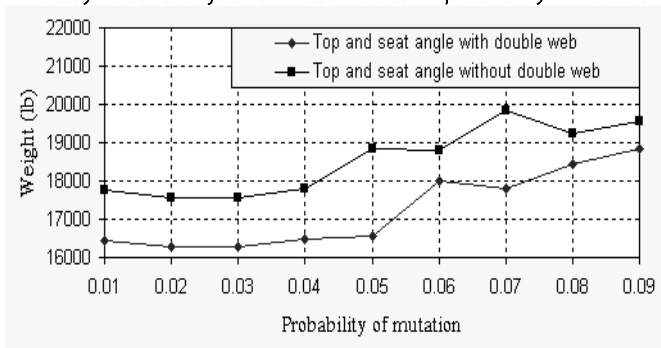

Figure 8. Study based on Probability of mutation

Through the study, the suitable GA parameters of this problem that optimum result is obtained are: popsize = 75-100; pc = 0.7-0.8; pm = 0.02-0.03.

The results obtained for designs with semi-rigid connection of the composite frame after tenth run are presented in Figure 9. The results of each run time are different, but the difference is quite small.

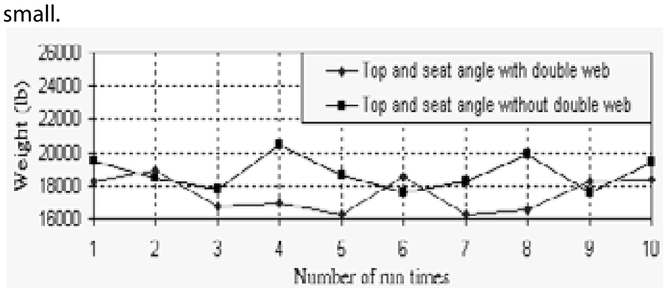

Figure 9. The results of 10 times running

The convergence characteristics of the weight of the frame were then examined during the optimization process are shown in Figure 10 while the corresponding design variables of the optimum solution are given in Table 1.

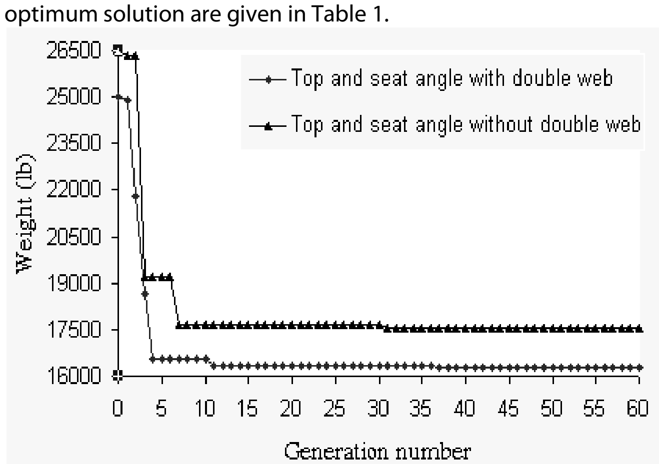

Figure 10. Convergence of Minimum Values of Objective Function

Table 1 lists the comparisons of the results from rigid and semi-rigid connections. It shows that frames with semi-rigid connections are heavier than ones with rigid connections, the frames with top and seat angle with and without double web are 4.1% and 11% heavier than the frame with rigid connections. However, the comparison between the semi-rigid connections reveals the fact that when a connection becomes more flexible, the frame becomes heavier. For optimal aspect, convergence of frame with rigid connections is sooner than semi-rigid connection frame.

Table 1: Comparison of Results for three-storey, two-bay composite frame

Group	Member type	(Rigid)	Top and seat angle with double web	Top and seat angle without double web
1	Column (C_1)	W 14 x 48	W 14 x 43	W 14 x 43
2	Column (C_2)	W 8 x 35	W 10 x 39	W 8 x 35
3	Column (C_3)	W 14 x 48	W 14 x 43	W 14 x 43
4	Column (C_4)	W 8 x 35	W 10 x 39	W 8 x 35
5	Column (C_5)	W 14 x 48	W 14 x 43	W 14 x 43
6	Column (C_6)	W 8 x 35	W 10 x 39	W 8 x 35
7	Beam	W 21 x 50	W 24 x 55	W 24 x 62
Number of connectors per beam		15	22	22
Weight (lb)		15630	16290	17562

Therefore, time to run the program is shorter. The reason is that the semi-rigid connection affects the displacement of the frame and brings about redistribution of moments between columns and beams. So the number of fit individuals being effective is quite a lot. It also causes the reproduction operator of the next generation to be effective. Obviously, if we are supposed that the connection is fully rigid, its actual behaviors may not be evaluated completely. For safety aspect, it is very risky when fully rigid is used for designing. For implementation aspect, it is not economic to make a fully rigid connection.

This example, one again, shows actual behaviors of connections. Thus, practically, the analysis and design of frames beam-to-column connections should be molded as semi-rigid connections.

6. CONCLUSIONS

In this paper, the semi-rigid behavior of beam to column connections is considered in the reliability analysis of the composite frames. Through it, the optimization problems are established. The numerical examples indicate the importance of the assumption of semi-rigid behavior of connections in the analysis of composite frames.

The Genetic Algorithm used in this study. Genetic Algorithm does not face difficulties in mathematic aspect, thus it can solve problems which are large space search. However, Genetic Algorithm is a method that has random characteristic. In order to find the good result, the program should be run several times. On the research, for this case, the GA parameters should be selected: population size = 75-100; probability of crossover = 0.6-0.8; probability of mutation = 0.01-0.05, the result will be best.

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