Optimization approaches in analysis and design

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Optimization of Support Structure for Reduction of Reaction Force of Roof of a School Gymnasium

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Abstract

An optimization method is proposed for stiffness design of RC columns of a school gymnasium to reduce the interaction forces between the steel roof and supporting structure under seismic motions. The objective function is the maximum force at the connections, which is evaluated using the response spectrum approach. Constraints are given for the total mass and the interstory drift angles of columns. The sizes of columns are optimized using a heuristic approach called simulated annealing. It is shown in the numerical examples that the maximum interaction force is drastically reduced to less than half of the reference model through optimization. Property of the optimal solution is investigated in detail based on the mode shapes, natural periods, and effective mass ratios.

Keywords: school gymnasium, seismic response, optimization, reaction force, response spectrum approach.

1. Introduction

Fracture around the connections between the roof and the columns in the supporting wall of a long-span structure was reported as a key issue in the recent earthquake disasters in Japan. Especially for a light-weight steel roof supported by stiff RC structure, deformation concentrates around the connections. Accordingly, slip occurs at the pin/roller supports, and the steel members exhibit plastic buckling and fracture. This kind of damage may be is due to vibration of cantilever columns in the gable wall as reported in Ref. [2, 3]. Therefore, it can be prevented by designing the roof and supporting structure simultaneously so that a global vibration mode dominates against seismic motions.

The first author proposed an optimization approach to design of the supporting columns of a long-span arch to reduce the responses of the arch [1]. It has been shown that flexibility rather than stiffness of the columns reduces the response of upper arch especially in the normal direction of the arch.

In this study, we propose an optimization method for stiffness design of RC columns of a school gymnasium to reduce the interaction forces between the steel roof and supporting structure under seismic motions in longitudinal direction. The objective function is the maximum force at the connections, which is evaluated using the response spectrum approach. Constraints are given for the total mass and the interstory drift angles of columns. The sizes of columns are optimized using a heuristic approach called simulated annealing. It is shown in the numerical examples that the maximum interaction force is drastically reduced to less than half of the reference model through optimization. The property of optimal solution to reduce the interaction force is investigated in detail from the mode shapes, natural periods, and effective mass ratios.

2. Optimization problem

Optimization problem is formulated to minimize the maximum value of shear force at the supports between the roof and columns of the supporting structure under seismic motions, which is hereafter simply called *support*. Objective function is the maximum value among the maximum shear force at the supports.

Let m denote the number of members, including beams and braces of the roof, connected to a support. The extension in the ith mode and the extensional stiffness of the jth member connected to the support are denoted by d_i and K_i, respectively. The displacement response spectrum and the participation factor of mode i are denoted by S_{Di} and β_i, respectively. The maximum shear force of the kth support is evaluated using the SRSS (Square-root of sum of squares) method of f modes as

$$R_k = \sqrt{\sum_{i=1}^{f}\left(S_{Di}\beta_i \sum_{j=1}^{m} K_j d_j \right)^2}\ , \quad (k = 1, \ldots, s) \tag{1}$$

where the shear forces of s supports on the walls in the transverse and longitudinal directions are evaluated. The design variables are the size of the longer edge, perpendicular to the wall, of RC columns denoted by $\mathbf{A} = (A_1, \ldots, A_t)$, where t is the number of design variables. Note that the ratio of the sizes of shorter and longer edges of column is fixed at the value of the initial design. The upper bound $\overline{\theta}$ is given for the maximum value of interstory drift angles $\theta_i(\mathbf{A})\ \ (i = 1, \ldots, t)$ of the columns. Optimization problem for minimizing the maximum shear force at supports is formulated as follows:

$$\begin{aligned} &\text{minimize} && \max(R_i, \ldots, R_s) \\ &\text{subject to} && \theta(\mathbf{A}) \leq \overline{\theta} \\ & && W(A) \leq \overline{W} \end{aligned} \tag{2}$$

where $W(\mathbf{A})$ is the total weight of columns, and $\overline{W}$ is its upper bound.

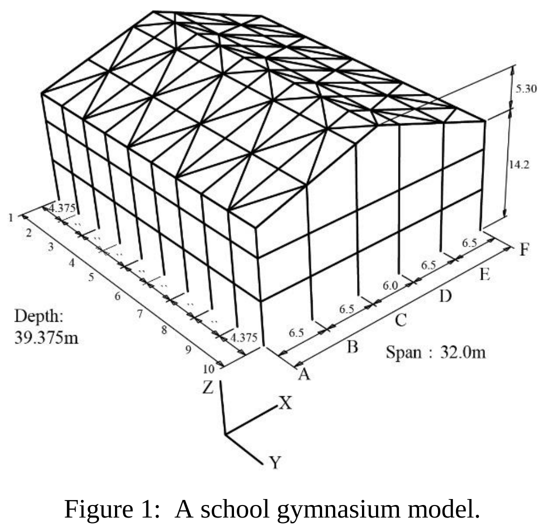


Figure 1: A school gymnasium model.

Table 1: Sections of beams and columns.

Column	Size (mm)	Beam	Size (mm)
RC: C1 (10,A)	700×900	RC: G82 (2F)	350×750
RC: C2 (10,B)	650×800	RC: G83 (3F)	650×750
RC C3 (10,C)	500×650	Steel: sG1 (roof)	H-700×300×13×24
RC: C4 (1,B)	650×800	Steel: sB (roof)	H-200×100×5.5×8
RC: C5 (1,C)	500×650	Steel: sV (roof)	L-65×65×6

3. Optimization result

Consider a school gymnasium as shown in Fig. 1, which is similar to the model in Refs. [2, 3]. The member sections are listed in Table 1, where H- a×b×c×d means a narrow-flange section with height *a*, width *b*, web-thickness *c*, and flange-thickness *d*. The materials of concrete and steel are Fc18 and SS400, respectively, in Japanese specification. Only the self-weight of members is considered for the vertical load.

The design acceleration response spectrum in Fig. 2 is used for evaluating seismic response using OpenSees [4]. The number of modes *m* is 40, and the seismic motion is applied in the longitudinal direction. Rayleigh damping is used with the damping factor $h = 0.02$ for the 1st and the 2nd mode. The spectrum in Fig. 2 is for damping factor $h = 0.05$, and it is scaled by the coefficient $F_h = 1.5/(1+10h)$.

Optimization is carried out using simulated annealing. The design variables are discretized into 501 equally spaced values with the upper and lower bounds ± 250 mm of the initial value. The upper bound $\bar{W}$ for the total weight of column is equal to the weight of the initial solution, and the upper-bound interstory drift angle is $\bar{\theta} = 1/800$.

The shear forces in longitudinal direction (*y*-direction) are evaluated at the ten supports of the roof as specified in Fig. 3. The horizontal displacements in transverse direction (*x*-direction) are released at supports 2 and 3, while others are pin-supported. The columns for the supports are C1 for No. 1, 4, 5, 6, 7, 8, and C2, C3, C4, C5 for No. 9, 10, 2, 3, respectively. Therefore, the number of variables is $t = 5$ utilizing symmetry condition.

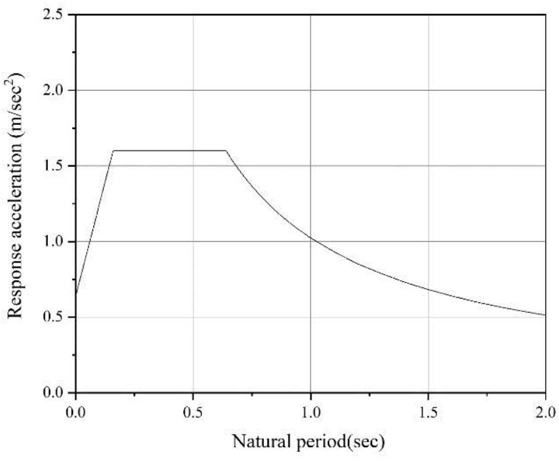


Figure 2: Design acceleration response spectrum.

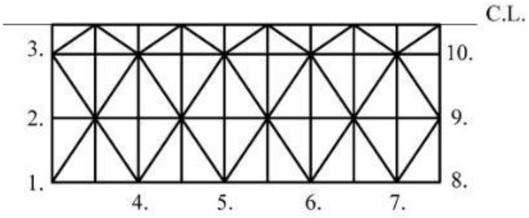


Figure 3: Support numbers of roof.

Table 2: Optimization results.

Column	Initial size (mm)	Optimal size (mm)
C1	900	936
C2	800	530
C3	900	575
C4	800	679
C5	900	830
Objective function (kN)	43.7	20.8
Total reaction force (kN)	208	117

Table 3: Comparison of effective mass ratio and natural period between initial and optimal solutions.

Initial solution			Optimal solution		
Degree	Effective mass ratio	Natural period (sec)	Degree	Effective mass ratio	Natural period (sec)
28	0.538	0.218	30	0.284	0.234
11	0.185	0.448	33	0.230	0.218
19	0.141	0.324	8	0.144	0.500

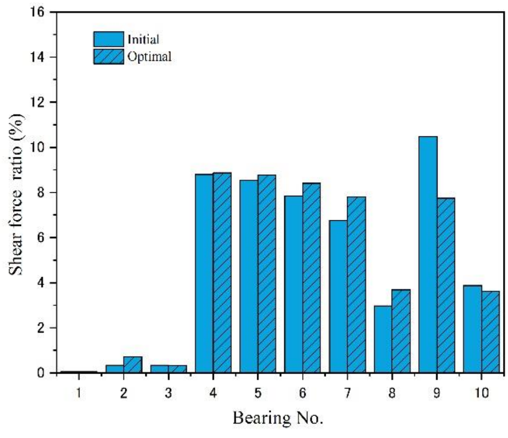
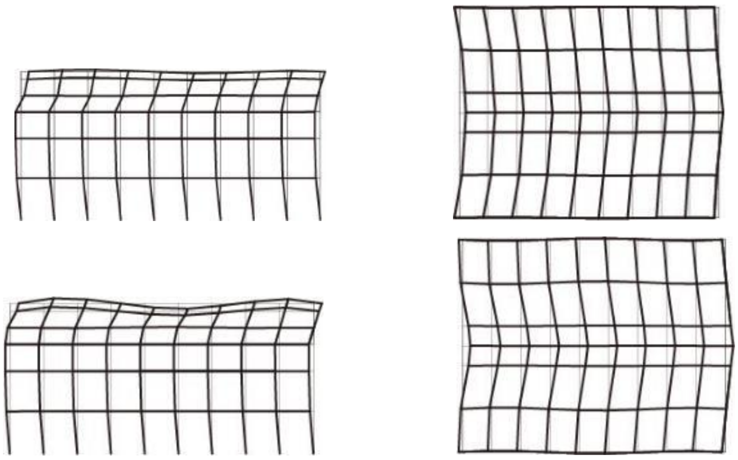


Figure 4: Ratios of shear forces to the total values for initial and optimal solutions.

Optimization results are shown in Table 2 along with the values of initial solution. As seen from the table, the size increases only in C1 that is located in the longitudinal wall. Therefore, the columns in the wall of longitudinal direction (longitudinal wall) have larger values than those in the transverse directions. The objective function, which is the maximum reaction force, is decreased to less than half of the initial value, and the sum of reaction forces is also reduced to almost half.

The three largest effective mass ratios and the corresponding natural periods of initial and optimal solutions are listed in Table 3. As seen in the table, no significant difference is observed in Table 3 in the natural periods of the modes corresponding to the largest effective mass ratios of initial and optimal solutions. A single mode dominates in the initial solution, whereas the two largest effective mass ratios of the optimal solution have close values. The ratios of shear forces to the total values for initial and optimal solutions, respectively, are shown in Fig. 4, which also confirms that the reaction forces of the optimal solution are more uniformly distributed than those of the initial solution. The vibration modes of the roof corresponding to the maximum effective mass ratios of the initial and optimal solutions are shown in Fig. 5.

It is seen from Fig. 4 that the out-of-plane vibration of the wall in the transverse direction (gable wall) dominates in the most excited mode of the initial solution, while the vertical vibration dominates in the optimal solution. This way, the vibration of the gable wall is suppressed and the seismic force of the roof is transmitted by the braces to the longitudinal wall.



(a) (b)

Figure 5: Shapes of most excited modes; (a) model 28 of initial solution, (b) mode 30 of optimal solution.

4. Conclusions

An optimization method has been proposed for reduction of the maximum shear force at the supports of the roof of a school gymnasium. The gymnasium is subjected to seismic excitation in the longitudinal direction. The responses are evaluated using the SRSS method.

It has been shown that the maximum shear force can be reduced to almost half of the initial solution by optimizing the sizes of the columns of the supporting structure. The shape of dominant mode is modified through optimization to suppress the out-of-plane vibration of the gable wall so that the seismic forces of the roof is transmitted through braces to the longitudinal wall.

References

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[4] Open System for Earthquake Engineering Simulation (OpenSees), PEERC, UC Berkeley ially in the early stage.