

# Optimum Design of Steel-framed House Structure Using Evolutionary Computing

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## Abstract

*Nippon Steel & Sumitomo Metal Corporation has developed high-performance steel bearing walls for steel-framed houses. The developed wall system enables construction of 4-story steel houses in seismic regions. However, the structural design of steel-framed houses becomes more complex as the number of stories increases. Therefore, an efficient design method for steel-framed house structures is strongly required. To this end, design methods for bearing wall arrangements and cross sections of cold-formed steel members are developed utilizing evolutionary computation methods such as the Genetic Algorithm and Differential Evolution. This paper first describes an overview of the developed design methods. The potential use of the developed design methods is also demonstrated through design case studies.*

## 1. Introduction

Steel-framed houses (an example is shown in **Photo 1**) are a housing system wherein bearing walls consist of light-gauge steel members (cold-formed steel channels or ripped channels) and wall panels that are fixed to each other by self-tapping screws. Nippon Steel & Sumitomo Metal Corporation has developed a bearing wall for higher seismic resistance by replacing the conventional wall panels (plywood board or gypsum board) with an improved wall panel (buckling stiffening steel sheet with burring holes). As a result, the application range for steel-framed houses has expanded from 2-storied to 4-storied buildings in seismic regions (**Photo 2**).<sup>1)</sup> Affected by the expanding of applicable stories, the structural design of steel-framed houses is becoming more complex, and an efficient design method is strongly required. Particularly, the design of an effective bearing wall arrangement, as well as the strength-enhancing design of the vertical member (stud) used in the bearing wall are important.

Concerning these subjects, we focused on the application of evolutionary computation, which is excellent in deriving global optimal solutions, and studied the design method of the bearing wall arrangement and cross section of the stud channel.<sup>2-5)</sup> This paper in-

troduces the design method of optimum bearing wall arrangement by using the genetic algorithm (hereinafter referred to as GA)<sup>6)</sup> and the design method of the optimum cross sectional dimensions of the ripped channel by using differential evolution (hereinafter referred to as DE)<sup>7,8)</sup>, and examples of the trial design thereof.

## 2. Optimum Design of Bearing Wall Arrangement by Using GA

### 2.1 Design of bearing wall for 4-storied, steel-framed house

Steel-framed houses employ the platform construction method



Photo 1 Steel framed house and cold-formed steel members

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Photo 2 4-storied steel framed house

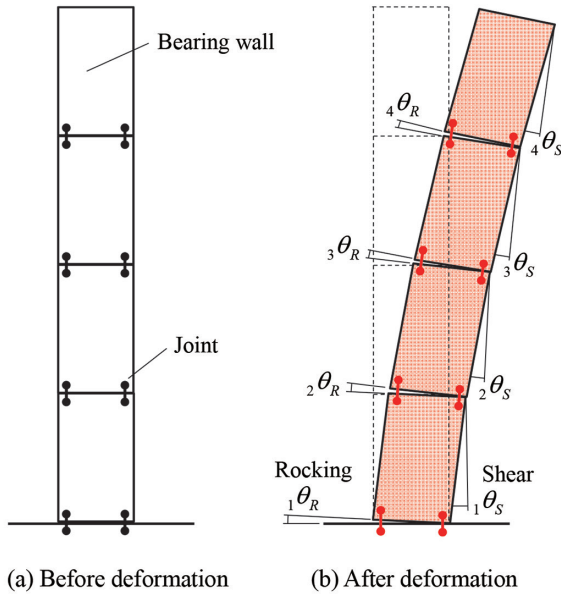


Fig. 1 Vertically aligned bearing walls

in which wall panels and floor panels are installed alternately and constitute a multi-story bearing wall (Fig. 1(a)) by connecting the leg of the upper-floor wall with the top of the lower-floor wall with joints. In the seismic design of a 4-storied, steel-framed house, response of the bearing wall is evaluated, taking into consideration the shearing deformation ( $\theta_S$ ,  $f = 1, 2, 3, 4$ ) of the wall panel and additionally the rocking deformation ( $\theta_R$ ) developed by the rotation of the leg of the bearing wall caused by the expansion and the contraction of the joint (Fig. 1(b)). This method, although effective in enhancing response evaluation accuracy, increases the design time of the bearing wall arrangement.

The conventional structural design of a 4-storied, steel-framed house is conducted in the following processes I–V.

- I. Set of design condition
- II. Tentative arrangement of bearing wall based on structural designers' experience (wall type, quantity of wall, position)
- III. Preparing a 3D frame model (Fig. 2 wherein bearing walls are replaced by braces and joints are replaced by nodal springs)
- IV. Computation by 3D frame analysis
- V. Comparison and evaluation of response of bearing wall (shear deformation, shear force) and wall capacities (shear rigidity, shear strength)

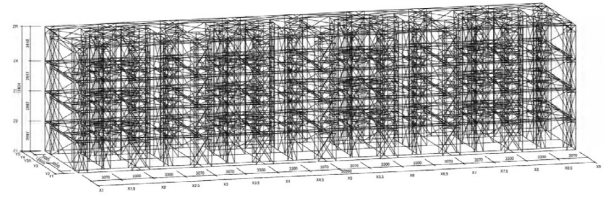


Fig. 2 3D frame model

Designers repeat the processes of II–V above on a trial-and-error basis, and explore the most optimized bearing wall arrangement that satisfies the seismic design requirement with the minimum wall quantity. However, because this design process requires a large work load, the number of repetitions of trial-and-error is limited in the actual design work. Without the repeated trial-and-error, the optimum design method derives the bearing wall arrangement plan that satisfies the design requirement with the smallest wall by the application of GA.

## 2.2 Formulation of optimum arrangement of bearing walls

In the optimum design of bearing wall arrangement for a 4-storied, steel-framed house, an optimization problem is set which explores the bearing wall arrangement that minimizes the wall quantity on condition that the bearing wall has no damage against occasionally occurring small/medium earthquakes and has controlled damage with energy absorption against quite rare large earthquakes<sup>9)</sup>. The optimization problem with constraint conditions is represented by the following formulae.

$$\text{Maximize } V \quad (1)$$

$$\text{Subject to } P \leq 1 \quad (2)$$

The maximized objective function is the value of fitness  $V$  that is determined as the inverse number of the total sum of the wall quantity. The constraint condition is based on the seismic design requirement in which penalty  $P$  below 1 is set in the case that the requirements are completely satisfied. Where fitness  $V$  is the product of  $V_X$  and  $V_Y$  determined in the directions of arrangement of the bearing walls (in the  $X$ -direction and  $Y$ -direction).

$$V = V_X \cdot V_Y \quad (3)$$

$$V_X = \left\{ \sum_{f=1}^4 \left( \sum_{i=1}^n L_{Xi} \right) f P_X^{a_X} \right\}^{-1} \quad (4)$$

$$V_Y = \left\{ \sum_{f=1}^4 \left( \sum_{j=1}^m L_{Yj} \right) f P_Y^{a_Y} \right\}^{-1} \quad (5)$$

Where,  $n, m$ : numbers of possible design areas (area where bearing walls are installable),  $L_{Xi}, L_{Yj}$ : width of bearing wall (suffix  $f$ : number of floors,  $X, Y$ : direction,  $i, j$ : number of possible designs areas),  $f P_X, f P_Y$ : penalty based on the judgment on the design requirement and  $a_X, a_Y$ : scaling coefficient magnifying penalty. The penalty is given as the product of the judgment value of items with respect to the seismic design requirement by the following formulae.

$$f P_X = f P_{XW} \cdot f P_{XD} \cdot f P_{XB} \cdot f P_{XE} \cdot f P_{XS} \cdot f P_{XWU} \cdot f P_{XBU} \cdot f P_{XF} \cdot f P_{XM} \cdot f P_{XL} \quad (6)$$

$$f P_Y = f P_{YW} \cdot f P_{YD} \cdot f P_{YB} \cdot f P_{YE} \cdot f P_{YS} \cdot f P_{YWU} \cdot f P_{YBU} \cdot f P_{YF} \cdot f P_{YM} \cdot f P_{YL} \quad (7)$$

Where, the suffix  $\Delta$  of the judgment value  $f P_{\Delta\Delta}$  denotes the direction of the arrangement of the bearing wall ( $X$  or  $Y$ ),  $\Delta$  denotes the following item of design requirement; with respect to the seismic design against small/medium earthquakes,  $W$ : strength of bearing wall,  $D$ : rigidity of bearing wall, and  $B$ : strength of joint; with respect to the seismic design against large earthquakes,  $E$ : ratio of eccentricity (eccentricity of center of rigidity from the center of gravity of the building),  $S$ : ratio of rigidity (ratio of rigidity between upper floor and lower floor),  $WU$ : strength of bearing wall,  $BU$ : strength of joint,  $F$  and  $M$ : bearing strength margin of each floor, and  $L$ : lower

limit value of average bearing wall width. The judgment value is taken as 1 (one) when the design requirement is satisfied, and when it is not satisfied, a value higher than 1 (one) of the ratio of the responded value vs. the design requirement value is given.<sup>2,3)</sup>

### 2.3 Application of GA

The specifications of the multi-story bearing wall are coded by the bit string of the binary number system (Fig. 3). The bit string expresses the width of the bearing wall ( $1.0P$ ,  $1.5P$ , ... with  $0.5P$  increments where  $P$  is the unit bearing wall width of 910mm), wall type (steel sheet with burring holes, cement board, none), upper limit floor number with arrangement of bearing wall (1st floor, 2nd floor, 3rd floor, 4th floor), and number of wall layers (single or double-layer) on each floor. By adding up together all the bit strings of each multi-story bearing wall, the whole bit string expresses the wall bearing arrangement of the entire building (Fig. 4). In the bearing wall arrangement planning, the following rules are set. They are: the bearing wall on the first floor is to be arranged within the width of the possible design area, the bearing wall on the 2nd–4th floor is installable only when the bearing wall exists in one of the lower floors.<sup>10)</sup> Furthermore, the widths of the upper and lower floor bearing walls should be the same, and the number of the wall layers should also be the same.

In the application of GA, 20 initial populations were set randomly. The selection procedure was based on the elite preservation strategy (the number of elite individuals is two) and the roulette wheel selection. In the genetic operator, the uniform crossover rate was set to 1.0 and the mutation rate was set to 0.02. The genetic operation was continued until final generation ( $G=500$ ).

### 2.4 Trial design of optimum arrangement of multi-story bearing wall

The multi-story bearing wall (panel height is 2730mm on all floors) of a 4-storied, multiple dwelling house for use as a dormitory (20 rooms/floor,  $17\text{m}^2/\text{room}$ ) is the subject of the trial design. Possible design areas common to all floors (Fig. 4) are set referring to their floor planning. The specifications (wall width, wall type, number of wall layers) of each bearing wall were arranged symmetrically according to the dwelling unit layout (shown with numbers ①–⑦ in Fig. 4). Under these conditions, the optimum bearing wall arrangement that satisfies the seismic design requirement with the minimum wall quantity was explored.

The following types of bearing walls were used: the wall with a steel sheet stiffened by burring hole for the 1st and 2nd floor (BW1: sheet thickness 1.2mm, BW2: sheet thickness 1.0mm), and the wall with cement board for the 3rd and 4th floor (NW1: screw pitch 150mm, NW3: screw pitch 200mm)<sup>1)</sup>. In the  $X$  direction where the possible design area of bearing walls is limited because of openings (windows and doors), the selection of either a single layer wall (no sign after the wall type symbol) or double layer wall (a sign of w after the wall type symbol) was allowed. In the  $Y$  direction where there is no opening, and the possible wall design area is sufficiently secured, only the single layer wall was allowed. Additionally, the joints that connect the upper floor wall and the lower floor wall are designed so as to withstand sufficiently the pull-out force and the pushing force exerted on the leg of the bearing walls.

As a result of the exploration, a solution that adheres to the bearing wall arrangement rules and satisfies the seismic design requirement was derived. The derived arrangement of the bearing wall on each floor (Fig. 5) stays within the design possible area (Fig. 4), and follows the arrangement restriction that the wall width and the number of the wall layers on the upper floor and those of the lower floor

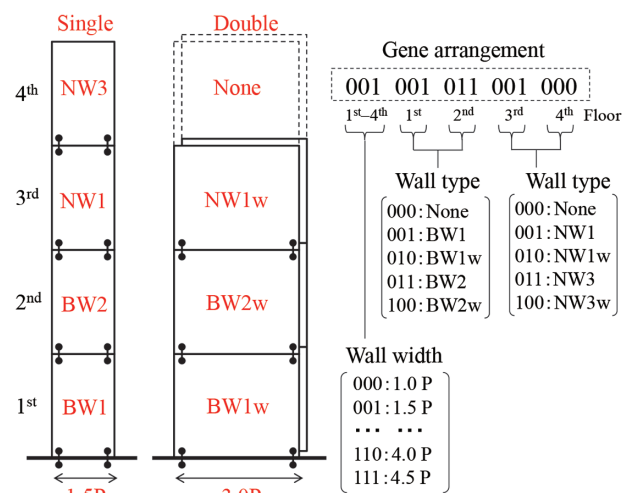


Fig. 3 Coding for bearing wall specification

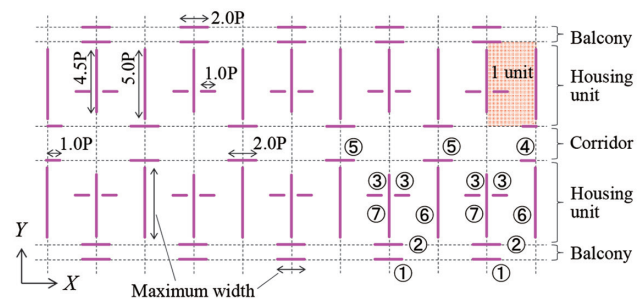


Fig. 4 Design possible area of bearing walls

need to be reconciled with each other. From the transition of fitness  $V$  (Fig. 6) of the fittest individual in a generation, it is judged that at around  $G=300$ ,  $V$  converges to a certain constant value and reaches the optimal solution. The penalty of the fittest individual in a generation (the maximum value of penalties on the 1st to 4th floors, Fig. 7) exceeds 1 (one) in the initial stage of calculation ( $G=1-50$ ), which converges to 1 (one) in the final stage. The transition of penalty indicates that a solution which satisfies all of the items of seismic design requirements has been obtained.

## 3. Optimum Design of Cross Sectional Dimensions of Ripped Channel by Using DE

### 3.1 Strength design of ripped channel under a compressive force

The optimum cross sectional dimensions of the ripped channel (Fig. 8) was studied. The ripped channel is the representative light gauge steel member for the steel-framed houses. When subjected to a large compressive force, the ripped channel experiences some type of buckling mode which is overall buckling mode wherein the entire member is bent and local buckling mode wherein the plate element is deformed out of plain and so on (Fig. 9). In the structural design of members, the cross sectional dimensions need to be determined by evaluating the compressive strength under the compounded mode of the above buckling modes.

The basic cross sectional dimensions of the ripped channel are shown in the product specifications of light gauge steel members<sup>11)</sup>. However, from the viewpoint of efficient structures, there's still room for optimizing the cross sectional dimensions. Hereinafter, a

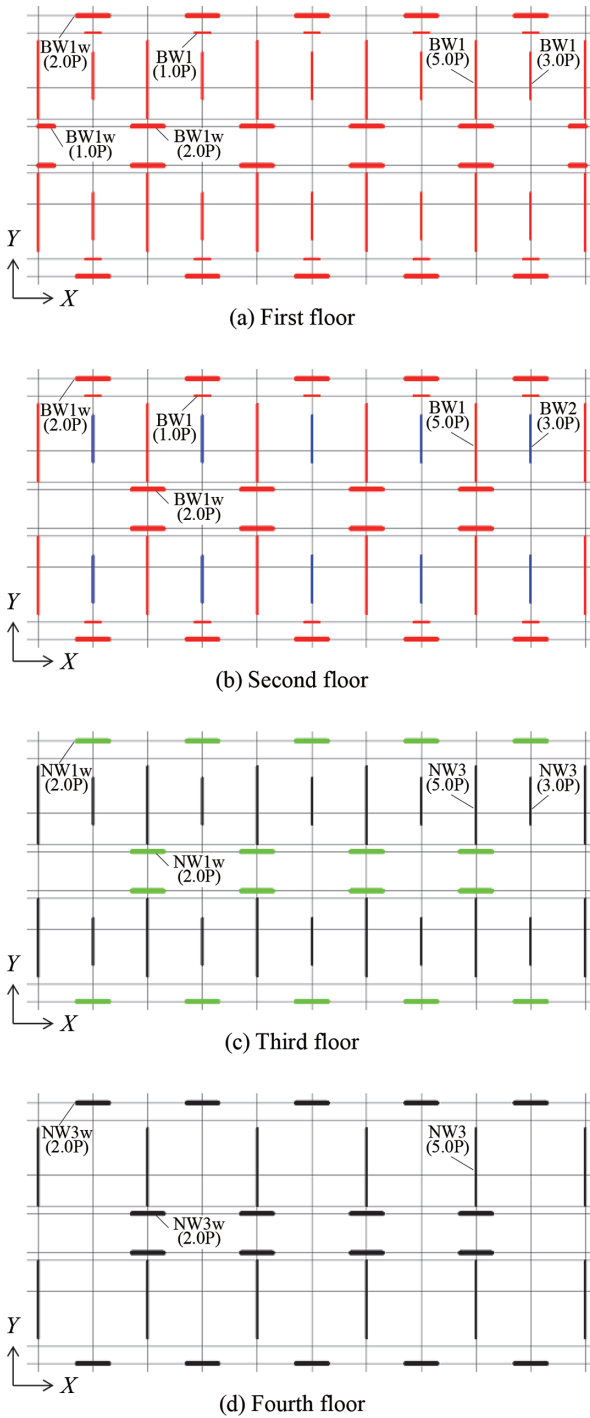


Fig. 5 Arrangement of bearing walls

case of using a ripped channel for the vertical frame of a bearing wall of steel-framed houses is studied, where the optimum cross sectional dimensions that maximize the compressive strength of the member under cross section area restrictions is derived by applying DE.

### 3.2 Formulation of optimum cross sectional dimensions

The design method of the optimum cross sectional dimensions to maximize the compressive strength of a ripped channel member

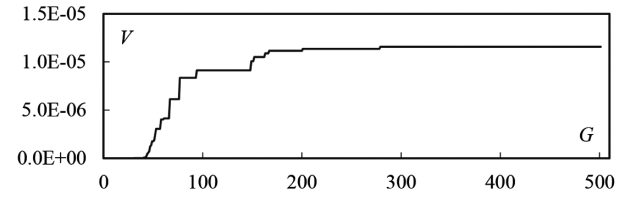


Fig. 6 Evaluation of fitness

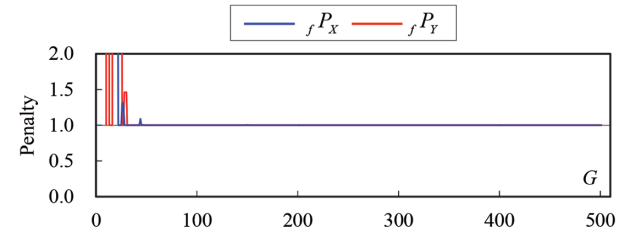


Fig. 7 Evaluation of penalty

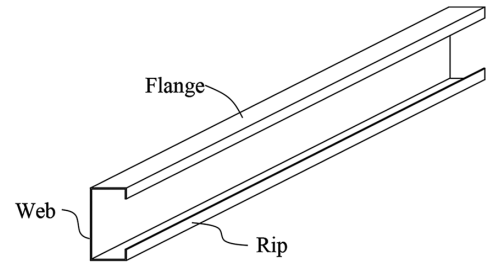


Fig. 8 Ripped channel

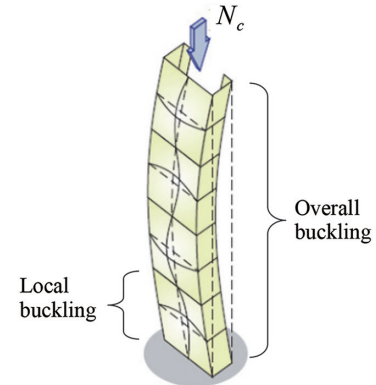


Fig. 9 Buckling modes considered in design

under a restricted cross section area is formulated as follows.

$$\text{Minimize} \quad 1/N_c(\mathbf{x}) \quad (8)$$

$$\text{Subject to} \quad A(\mathbf{x}) = A_0 \quad (9)$$

$$\mathbf{x} = \{x_1, x_2, \dots, x_n\} \quad (10)$$

Where,  $N_c$ : compressive strength of member,  $A$ : cross section area,  $A_0$ : restricted cross section area,  $x_i$  ( $i=1, 2, \dots, n$ ): design parameter that determines cross sectional dimensions, and  $n$ : dimension of parameter.

### 3.3 Calculation of compressive strength of ripped channel member

The compressive strength of a ripped channel member under a



compressive force in the axial direction is calculated based on the elastic buckling strength corresponding to buckling mode. The elastic buckling strength is obtained by the eigenvalue buckling analysis of the finite strip method (hereinafter referred to as FSM)<sup>12)</sup>. The values of the elastic buckling strength obtained by FSM, yield strength of the steel and the cross section area of the member are put into the strength formula of the direct strength method (DSM)<sup>13)</sup>, and the compressive strength of the member  $N_c$  is calculated.

### 3.4 Exploration of cross sectional dimensions by DE

The dimensions of the web height  $h$ , flange width  $b$  and the rip length  $c$  of the cross section of a ripped channel (Fig. 10) are explored by DE, wherein the shape of the cross section is symmetrical with respect to the web height direction, and the dimensions of the paired flange width and the rip length are equal. Furthermore, the sheet thickness  $t$  is constant in the entire cross section. The developed length of the cross section is expressed by  $S (=h+2b+2c)$ . The web height  $h$  is defined as the product of the design parameter  $x_1$  and the developed length  $S$ , and similarly, the flange width  $b$  is defined as the product of the design parameter  $x_2$  and the developed length  $S$ . Additionally, the rip length  $c$  is determined as half of the length of  $S$  with the subtraction of web height  $h$  and a double size of the flange width  $2b$  therefrom.

$$h = x_1 \cdot S \quad (11)$$

$$b = x_2 \cdot S \quad (12)$$

$$c = (1 - x_1 - 2x_2) S / 2 \quad (13)$$

Where,  $h$  and  $b$  are the positive values below  $S$ , and the ranges of  $x_1$  and  $x_2$  are defined as follows.

$$\begin{aligned} 0 < x_1 < 1 \\ 0 < x_2 < 1 \end{aligned} \quad (14)$$

In addition, the rip length is restricted as follows so that it becomes a positive value and does not exceed half of the web height to avoid rip overlapping. In the case that this condition is not satisfied, a large value ( $1/N_c=1$ ) is given to the objective function  $1/N_c$  forcibly to exclude the case from the candidates for the optimal solution.

$$0 < 1 - x_1 - 2x_2 < x_1 \quad (15)$$

In this study, as the developed length  $S$  is determined by dividing the restricted cross section area  $A_0$  by the sheet thickness  $t$  ( $S=A_0/t$ ), the restricting condition of formula (9) is always satisfied.

The basic algorithm of DE, that is, DE/rand/1/bin<sup>7)</sup> is applied, and the design parameters  $x_1$  and  $x_2$  that minimize the objective function  $1/N_c$  (maximize compressive strength  $N_c$ ) are explored.

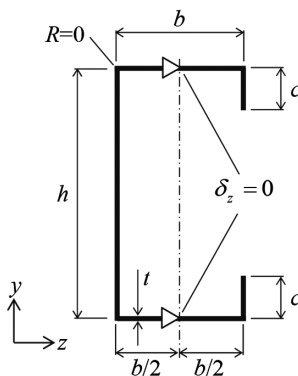


Fig. 10 Cross section of a ripped channel

### 3.5 Trial design of optimum cross sectional dimensions of ripped channel

Relative to a ripped channel member 2730mm in length assumed to be used as the vertical frame of a bearing wall for steel-framed houses, the cross sectional dimensions that maximize the compressive strength  $N_c$ , were explored for the cases of steel sheet thickness  $t$  of 1.0mm, 1.2mm, 1.4mm and 1.6mm. The restricted cross section area  $A_0$  was determined as 202mm<sup>2</sup> based on the dimensions of the ripped channel 89LCM10 ( $h=89$ mm,  $b=44.5$ mm,  $c=12$ mm and  $t=1.0$ mm) in the product specifications<sup>11)</sup>. In this study, the cross sectional dimension shows the size between the centers of sheet thickness, and the radius of bend is zero. Furthermore, considering that in the vertical frame of a bearing wall the flange of the ripped channel is screw-fixed to the wall panel, the displacement of the center of the flange in the sheet-width direction is restricted ( $\delta_z$  in Fig. 10). In the application of DE, the number of populations  $N_p=20$  and maximum generation  $G_{max}=100$  were set. As parameters for implementing genetic operation, the mutation rate of  $F=0.70$  and the crossover rate of  $C_r=0.50$  were used, referring to the study of Kitayama et al.<sup>8)</sup>

The progress of the populations of the design parameters ( $x_1, x_2$ ) is shown in Fig. 11, where the horizontal axis is of  $x_1$  which indicates the web height  $h$ , and the vertical axis is of  $x_2$  which indicates the flange width  $b$ . The contour lines show the solution space of the objective function  $1/N_c$  (drawn by varying  $x_1$  and  $x_2$  at 0.01 pitch). Initial populations were generated randomly ( $G=1$ ), and each individual of the group moved toward the concaved section of the contour line with the elapse of generation ( $G=17$ ), then all individuals ultimately converged at the point which is considered as the global optimal solution ( $G=100$ ). The transition of the objective function  $1/N_c$  (minimum value in a generation) is shown in Fig. 12 for the sheet thickness  $t$  of 1.0mm. As the exploration progresses,  $1/N_c$  decreases gradually, stays at a constant value after the generation of around  $G=30$ , and the solution converges.

The optimum cross sections of the ripped channel are shown in Fig. 13, and their dimensions and the compressive strength are shown in Table 1. The compressive strength of the optimum channel is higher than that of the original ripped channel (89LCM10) in all sheet thickness categories. Although in the sheet thickness  $t=1.0$ mm category, increase of the compressive strength is only 3%, the compressive strength increases remarkably as the sheet thickness increases. When the sheet thickness  $t$  is 1.6mm, the compressive strength increases by 27%. This result suggests that even under the condition that the cross section area is unchanged, the compressive strength of a ripped channel can be enhanced by setting the cross sectional dimensions optimally in accordance with sheet thickness.

## 4. Conclusion

In order to clarify the efficient structural design of steel-framed houses which expands its application from 2-storied to 4-storied, we studied the optimum bearing wall arrangement design and the optimum cross sectional dimensions design of the vertical frame by applying the evolutionary computation method. The wall arrangement plan capable of optimizing the combinations of the bearing wall specifications (width, type, applicable floors and number of layers), satisfying the seismic design requirement and minimizing the bearing wall quantity can be derived by applying GA. Furthermore, by applying DE, the optimum cross sectional dimensions (web height, flange width and rip length) of a ripped channel that maximize the

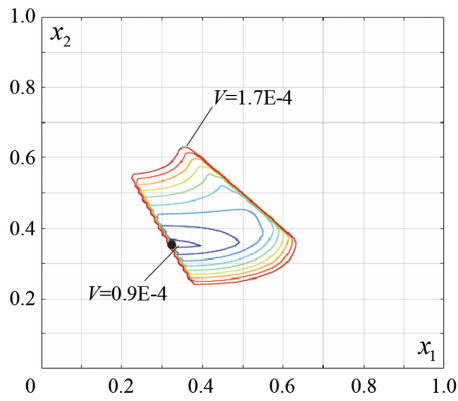
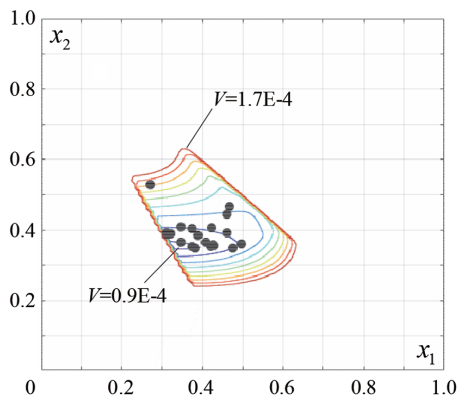
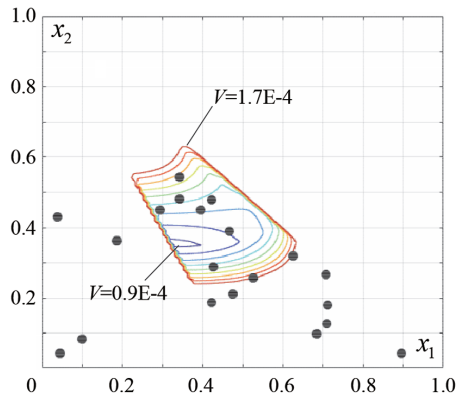


Fig. 11 Progress of populations in solution space

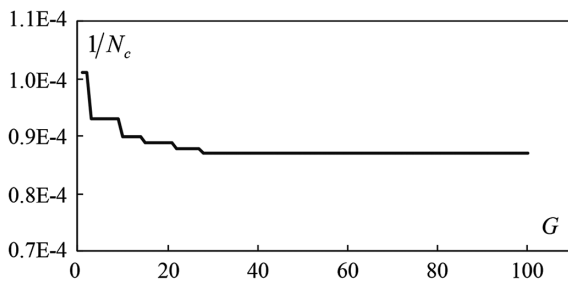


Fig. 12 Evaluation of objective function

Original	Optimization			
$t=1.0$	$t=1.0$	$t=1.2$	$t=1.4$	$t=1.6$
$b=44.5$ $h=89.0$ $c=12.0$	$b=53.9$ $h=74.9$ $c=9.7$	$b=41.9$ $h=70.7$ $c=6.9$	$b=24.8$ $h=82.1$ $c=6.3$	$b=10.3$ $h=91.7$ $c=7.0$

Fig. 13 Optimized cross section

Table 1 Section size and member strength

Type	Section size						Strength	
	$t$ (mm)	$h$ (mm)	$b$ (mm)	$c$ (mm)	$S$ (mm <sup>3</sup> )	$A$ (mm <sup>2</sup> )	$N_c$ (kN)	Ratio
Original	1.0	89.0	44.5	12.0	202.0	202.0	29.6	1.00
Optimization	1.0	74.9	53.9	9.7	202.0	202.0	30.4	1.03
	1.2	70.7	41.9	6.9	168.3	202.0	34.4	1.16
	1.4	82.1	24.8	6.3	144.3	202.0	37.0	1.25
	1.6	91.7	10.3	7.0	126.3	202.0	37.5	1.27

compressive strength in the axial direction can be derived for different sheet thickness under restricted conditions of the cross section area.

The practical design system for the optimum bearing wall arrangement has already been completed, and its application to actual projects will be promoted. On the other hand, the optimum design of cross sectional dimensions will be developed to practical methods, taking into consideration the restrictions on dimensions imposed by forming and assembling.

#### Acknowledgements

We hereby wish to express our utmost gratitude to Messrs. Shinji Tanemori, Takashi Ishida and Keisuke Mizokami of the NS Plant Designing Corporation for their cooperation in the programming of optimum design for the study.

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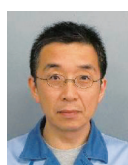
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