Optimal Design and Seismic Resistance of Reinforced Concrete Structures Braced with Shear Walls

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Abstract. This study optimized a building structure braced with shear walls using the CAFE software. First, the position of shear walls and initial design of shear wall thickness were decided. Preliminary analysis was conducted using the ETABS (extended 3D analysis of building systems) software to confirm the feasibility of the initial design. Subsequently, the influence of beam–column elements and shear walls on structural mechanics was explored. Next, this study proposed the optimal and most economical design of the structure of the building braced with shear walls. Finally, the relationship between the seismic resistance and optimization was identified.

1. Introduction
In Taiwan, reinforced concrete (RC) structures with shear walls are predominantly designed using conventional methods, which involve making assumptions, analyzing, checking, adjusting, reanalyzing, and rechecking before a design is finalized. However, such a finalized design by designers is not the most economical solution. Therefore, this study explored the optimal design model of RC building structures with shear walls from the perspective of seismic resistance.

2. Analysis methods
From the perspective of seismic resistance, this study employed the CAFE software to investigate the optimal design of RC building structures with shear walls. CAFE was developed by Yeh [1] and is an optimal mathematical analysis software constructed using a neural network method accompanied with cross-validation and training and testing.

The optimization model is as follows [1]:

- Objective function: to produce the optimal and most economical design with a focus on seismic resistance.
- Design variables: section sizes of beam–column elements as design variables, which are considered as discrete variables, for optimizing design.
- Constant variables: height of each story, shear wall layout, beam–column layout, and unit prices of concrete and reinforcing steel of various strengths.
- Constraints: reinforcement ratio and stiffness constraints.

Equivalent column model used for RC shear walls (figure 1): when using an equivalent column method to simulate RC shear walls, the equivalent column is determined by the edge column of the
wall, and material parameters should also be inputted based on their actual properties. The coupling beams on the top and bottom of the RC shear wall are simulated using steel beams [2].

![Figure 1. Equivalent Column Model of an RC Shear Wall [2].](image)

The CAFE software is used to analyze optimization problems of constrained or unconstrained functions. When managing constrained optimization problems, CAFE employs an indirect method, the exterior penalty function method, to convert this function into unconstrained optimization problems. The principles of the exterior penalty function method are transforming a constrained function into pseudo–objective functions for an unconstrained optimization problem by penalizing and modifying its constraints. Increase in a penalty coefficient enables an optimal solution of a modified unconstrained optimization to approach the feasible region. For unconstrained optimization problems, the CAFE software analyzes using a nonlinear-programming, derivative-free local search method, whose principles are as follows: (1) generating design variables randomly in a search region and setting them as initial designs; (2) calculating the objective function and repeating steps (1) and (2); (3) producing an optimal solution based on the objective function value; and (4) reducing the search area, repeating steps (1) through (3) $N$ times, and outputting an optimal solution [1–3].

Model analyses were used in CAFE to understand the influence of each input variable on the output variables. Different from a regression analysis model, which is a simplified function comprising regression coefficients, a neural network model does not reveal input and output variables clearly from the connection weights and threshold values. To solve the problem, two analysis approaches, specifically main effect plots and sensitivity analysis, are incorporated into the CAFE software. Moreover, in CAFE, models are improved through parameter optimization, which effectively solves the existing problems of the neural network method. The flow chart of the CAFE software optimization is shown in figure 2 [1, 3-5].
3. Case study
This study investigated a case of a ten-story RC building (occupancy importance factor $I = 1$); the floor layout of the building was 24 m in length and 24 m in width, and the building was 33.3 m high. The building structure had three spans each in the X and Y directions; each span measured 8 m. The first story was 4.5 m high, and the second through tenth stories were each 3.2 m in height. The shear walls were arranged in the X direction at the middle spans, as presented in figure 3. The strengths of the concrete and reinforcing steel were 280 kgf/cm² and 4200 kgf/cm², respectively. Focusing on improving seismic resistance, this study generated the optimal and most economical design, and the measurements of each component are listed in Tables 1–3. The capacity spectrum used for pushover analysis is shown in figures 4 and 5. Figure 4 reveals that the spectral displacement (Sd) and spectral acceleration (Sa) of the initial design at yield were 1.540 and 0.181, respectively. At collapse, Sd was 8.553, and Sa was 0.309. As shown in figure 5, the optimal design had an Sd of 3.721 and Sa of 0.279 at yield, and an Sd of 9.687 and Sa of 0.337 at collapse. The pushover analysis result of the structure braced with shear walls is presented in Table 4 [2].
Figure 3. Floor plan of the ten-story RC building structure braced with shear walls.

Figure 4. Capacity spectrum of the initial design of the structure braced with shear walls.

Figure 5. Capacity spectrum of the optimal design of the structure braced with shear walls.
Table 1. Sizes of the interior and exterior beam sections (size unit: cm).

| Floor | Interior beam sections | | Exterior beam sections | |
|-------|------------------------|--------|------------------------|--------|
|       | Original size          | Optimal size | Original size          | Optimal size |
|       | Depth | Width | Depth | Width | Depth | Width | Depth | Width |
| 10F   | 75    | 50    | 50    | 25   | 75    | 50    | 40    | 20    |
| 9F    | 75    | 50    | 54    | 27   | 75    | 50    | 44    | 22    |
| 8F    | 75    | 50    | 54    | 27   | 75    | 50    | 40    | 20    |
| 7F    | 75    | 50    | 52    | 26   | 75    | 50    | 40    | 20    |
| 6F    | 75    | 50    | 52    | 26   | 75    | 50    | 40    | 20    |
| 5F    | 75    | 60    | 50    | 25   | 75    | 60    | 42    | 21    |
| 4F    | 75    | 60    | 50    | 25   | 75    | 60    | 40    | 20    |
| 3F    | 75    | 60    | 48    | 24   | 75    | 60    | 40    | 20    |
| 2F    | 75    | 60    | 48    | 24   | 75    | 60    | 40    | 20    |
| 1F    | 75    | 60    | 50    | 25   | 75    | 60    | 40    | 20    |

Table 2. Sizes of the column sections (size unit: cm).

| Floor | 10F | 9F | 8F | 7F | 6F | 5F | 4F | 3F | 2F | 1F |
|-------|-----|----|----|----|----|----|----|----|----|----|
| Original size | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| Optimal size  | 49 | 54 | 55 | 55 | 65 | 66 | 68 | 68 | 71 | 84 |

Table 3. Thickness of shear walls (size unit: cm).

| Floor | 10F | 9F | 8F | 7F | 6F | 5F | 4F | 3F | 2F | 1F |
|-------|-----|----|----|----|----|----|----|----|----|----|
| Original size | 20 | 20 | 20 | 20 | 20 | 25 | 25 | 30 | 30 |
| Optimal size  | 10 | 10 | 10 | 10 | 10 | 12 | 14 | 16 | 18 | 22 |

Table 4. Pushover analysis of the structure braced with shear walls.

|                      | Yield displacement (cm) | Yield seismic force (t) | Ultimate displacement (cm) | Ultimate seismic force (t) | Toughness | External force coefficient | Seismic resistance performance Ap (g) |
|----------------------|-------------------------|-------------------------|-----------------------------|----------------------------|-----------|---------------------------|-------------------------------------|
| Initial design       | 2.29                    | 946.48                  | 12.70                       | 1617.9                    | 5.55      | 1.71                      | 0.263                               |
| Optimal design       | 5.624                   | 1144.13                 | 14.642                      | 1381.12                   | 2.60      | 1.21                      | 0.280                               |

4. Conclusion
This study applied the neural network method to optimize a building structure braced with shear walls and evaluated the structure’s seismic resistance using software equipped with pushover analysis tools. Finally, the correlation between the structure’s optimal design and its seismic resistance was explored, and the following conclusion was proposed [2]:

- Based on the evaluation of the seismic resistance of the structure braced with shear walls, optimizing beam size, column size, and shear wall thickness produced greater seismic resistance than optimizing only beam size and column size.
The relationship between the optimization of the structure braced with shear walls and seismic resistance suggested that during the optimization process of beam size and column size, beam size optimization had a higher contribution to $A_p$ values and was relatively more economical compared with column optimization.

According to the relationship between the optimization of the building structure braced with shear walls and the structure’s seismic resistance, the predicted optimal design values generated using the CAFE software demonstrated higher $A_p$ values and were more economical than those generated using a heuristic interactive method.

References

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