Design and Analysis of Single Opening Shear Wall Using Response Surface Methodology

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Abstract

The structural nonlinearity of reinforced concrete (RC) walls has been well studied in the past few decades. In Taiwan, Sung and Tsai et al. (2008) proposed a seismic capability assessment system for reinforced concrete buildings, SERCBWin2008. The nonlinear behavior of RC walls w/o openings was determined by softened strut and tie model in the system. However, based on basic functionality, most of the buildings with opening RC walls make the engineers trouble in structural analysis not only on problem of precision but also numerous computer time via conventional finite element method (FEM). To provide a precious and rapid analysis result, this paper used the response surface method (RSM) to make a regression analysis for establishing the relationship between some necessary parameters of walls and structural analysis results obtained by ANSYS 14.5. The correlation of structural nonlinearity between the walls w/o opening and with opening is able to be obtained. A satisfactory result of structural nonlinearity for the opening RC walls can be determined soon just via a simple modification to those of the walls w/o opening, based on the results obtained.

Keywords: RC wall with Opening, Response Surface Methodology, SERCB, ANSYS

1. Introduction

Kaohsiung Meinong earthquake in 2016, the collapse of the Golden Dragon building causing heavy casualties. One of the reasons is there are only a few walls on the first floor; only columns could use to resist seismic force. Low stiffness compared to other floors, the damage concentrates here to form a weak layer and then causes structural damage collapse, so the RC wall to the building's earthquake resistance contribution is particularly significant. In Taiwan, RC walls are being used for the residential and commercial buildings, most of its structure would be built many cubicle walls and external walls. Based on the use of demand, often with a large number of doors, windows, and air-conditioning holes, when the wall has opened, its seismic resistance would be reduced, and the opening size, opening position, and opening amount could have a critical impact on the earthquake resistance.

At present, there are many experts study on opening RC wall of the earthquake-resistant behavior, but in Taiwan's existing specifications are not clearly defined, so engineers often ignore the resistance of the opening RC wall. However, for a detailed assessment of the structure of the earthquake resistance, the opening RC wall should be considered. Sung and Tsai have proposed the no-opening RC wall using soften the compression-tension truss model as the basis, considering the mechanical characteristics of the three elements, which are horizontal rebar, vertical rebar, and concrete, add individually. The establishment of the equivalent diagonal brace along the diagonal frame direction is to resist the lateral force, and the equivalent diagonal brace has considered the concrete and rebar compression and tension of the mechanical behavior. The primary purpose is to analyze the use of low walls and simplify the wall simulation with accurate analysis results. The results are obtained by the SERCBWin2008 program for engineers to apply for structural analysis. Hwang et al. proposed to predict the base shear force-displacement curve of the opening RC wall under the shear failure control mode, which is tied to its cracking point, strength point, and limit point as the turning curve.

The primary purpose of this paper is to establish the relationship between the shear strength and horizontal displacement of the no-opening and opening RC wall. The opening RC wall uses the SERCB program to analyze the base shear force-displacement relationship, which can reduce the time required for structural analysis, and the opening RC wall using the Response Surface Method (RSM) theory and ANSYS finite element model analysis to obtain the force and deformation behavior under the lateral force. Apply the results to calculate the shear force-displacement reduction coefficient for the opening RC wall. The response surface function is established to replace the complex structure analysis using the RC wall material parameters, opening size, and position as input values, and the reduction coefficient is the output value. The engineer can be quickly and accurately analyzing the no-opening and the opening RC wall of the structure.

2. Finite element simulation of opening RC wall

The finite element method applied to the analysis of structures in civil engineering is quite mature, but the failure mode of opening RC walls is more complicated than no-opening RC walls, and the number of nodes and elements of opening RC walls is numerous. The overall calculation time is quite significant. Therefore, this paper develops a finite element model based on the statistical response surface method (RSM) theory, reflects on the opening RC wall model, and establishes a reduction relationship with the no-opening RC wall. It is used to calculate lateral and displacement, which can effectively improve the calculation efficiency.

2.1 Box-Behnken Design

The response surface method (RSM) proposed by BOX and Wilson in 1951 based on statistical theory and experimental design. The basic concept is fitting the relationship between system input (design parameters) and output (wall reaction) through data and regression analysis to obtain the mathematical function. Application of RSM to civil engineering, design parameters can be used as input, the system is a finite element model, and the output is a wall property or reaction by finite element analysis. Replacing the finite element model by response surface method (mathematical model) that fits the design parameters and the reaction of the wall, which can effectively improve the calculation efficiency.

Box-Behnken Design is designed to solve system problems with 3 levels and can fit first-order, first-order interaction cyclones, and second-order polynomials. In this study, a total of 62 experimental points was used for 7 factors, and the response surface model must find out the close relationship between the real system and the design variable, and the polynomial model is commonly used as the response surface model. Suppose the response surface is y, the design variable is $x_i\left(i=1,2,3,\ldots,k\right)$, the second-order model must be used if there is a curvature problem in the system:

$$y=\lambda_0+\sum_{i=1}^{k}\lambda_i x_i+\sum_i\sum_j\lambda_{ij}x_i x_j+\sum_{i=1}^{k}\lambda_{ii}x_i^2+\varepsilon\ \left(i\neq j\right) \tag{1}$$

where λ_0 、 λ_i 、 λ_{ii} 、 λ_{ij} are the undetermined coefficient.

It mainly discusses whether the accuracy of the response surface function obtained by regression analysis is sufficient to represent the real system (finite element model). Based on the output (analysis) results of the finite element model and the response surface function, a commonly used method to inspect the accuracy of the response surface function is R^2. Inspect method shows in Eq. (2):

$$R^2=1-\frac{\sum_{i=1}^{n}\left[y_{FEM}\left(i\right)-y_{RSM}\left(i\right)\right]^2}{\sum_{i=1}^{n}\left[y_{FEM}\left(i\right)-\bar{y}_{FEM}\right]^2} \tag{2}$$

In the formula, $y_{RSM}\left(i\right)$ is the result of the calculation of the response surface function, $y_{FEM}\left(i\right)$ is a finite element analysis calculation results, $\bar{y}_{FEM}$ is the average of the results of the finite element analysis calculation, n represents the number of inspection points in the design space and is also the number of experimental points for experimental design.

When R^2 less than 0.6, even closer to 0, indicating that at least 40% of the arguments can't show the variation of the corresponding variables, the regression results reference value is not high. Instead, when R^2 is closer to 1, the better the result of the regression analysis. If R^2 closer to 1 represents the input and output relationship of the response surface function in the experimental design space, which can accurately describe or represent the finite element model.

2.2 The establishment of ANSYS finite element model

The constitution law of concrete is based on the definition of Kawashima, and calculates the stress-strain curve relationship between the concrete confined by the boundary component and the unconfined concrete wall. The simulation of concrete in the RC wall uses Solid65 element, and its element cross-section property is to allow the definition of up to three different reinforcing materials evenly distributed on one element at different angles. This unit allows four different materials at the same time. Therefore, the reinforcement is simulated on the Solid65 concrete material in the form of a reinforcement volume ratio.

Because concrete has the ability to crack, crush, plastic deformation and creep, reinforced material can only withstand the compression and tension, can not bear shear force. To simulate the cracking and crushing behavior of concrete, according to Willam-Warnke failure theory, the shear force transfers coefficient of the crack in the RC wall and the shear transfer coefficient of the closed crack were taken at 0.35 and 1 respectively.

The simulation of the reinforced concrete wall regards the bottom as a foundation with greater stiffness, which is a rigid foundation, and there is no horizontal, vertical displacement, and rotation deformation. When the reinforced concrete wall modal was established in ANSYS, the axial force uniformly added on the top surface of the model, and push over analysis was performed with the lateral force applied on the boundary component using displacement control.

3. Design of opening RC wall

Taiwan's specifications do not indicate the strength and displacement of opening RC walls, according to the Japan Institute of Architecture「Reinforced concrete structural calculation standards」article 19 provides for the shear strength of the opening RC wall Q_{AO} calculated by multiplying the shear strength of the no-opening wall Q_A by the reduction coefficient r, such as shown in Eq. (3), but the Japanese specification does not consider the influence of different opening positions.

$$Q_{AO} = rQ_A \tag{3}$$

$$r = \min(r_1, r_2, r_3) \tag{4}$$

$$r_1 = 1 - \frac{\sum l_0}{\sum l} \tag{5}$$

$$r_2 = 1 - \sqrt{\frac{\sum h_0 \sum l_0}{\sum hl}} \tag{6}$$

$$r_3 = 1 - \frac{\sum h_0}{\sum h} \tag{7}$$

In the formula, r_1 is considering the reduction factor of the opening length, r_2 is considering the reduction factor of the opening area, r_3 is considering the reduction factor of the opening height, l_0 is the sum of the projected length of the opening, h_0 is the sum of the projected heights of the openings, l is the length of the wall, h is the height of wall.

3.1 Material parameter design

Based on the finite element model of the response surface method (RSM), the experimental design method was selected as Box-Behnken Design, and an opening RC wall model with boundary component was designed as shown in Fig.1. Considering the height-width ratio of the RC wall (H/L), ratio of compressive strength of concrete to shear strength of RC wall (f_c'/f_y), reinforcement ratio of wall (ρ_{wall}), lateral projection length of single opening and total wall length (Lop/L), projection length of single opening and total wall height (Hop/H), lateral starting position of single opening RC wall is (X) and single opening RC wall longitudinal starting position is (Y), there are 7 parameter designs in total, and 62 experimental points (the number of analysis groups). These seven design variables are normalized to three levels (-1,0,1) as shown in Table 1. Among them, the model simulations are all based on the design commonly used in engineering. The boundary component size is assumed to be $60 \times 60cm$; the reinforcement ratio is 3%; the compressive strength of the concrete is $f_c' = 280kgf/cm^2$, and the yielding strength of the reinforcement is $f_y = 4200kgf/cm^2$; the dimensions of the opening RC wall model assume a fixed length $300cm$, thickness $15cm$, height based on its height-width ratio, and this study only considers that the wall height-width ratio

H/L is between 0.5 to 2. The compressive strength of the concrete f_c' is between $140 \sim 420kgf/cm^2$, the reinforcement yielding strength is between $2800 \sim 4200kgf/cm^2$, and the reinforcement ratio ρ_{wall} is between 0.002 and 0.0025 according to the national reinforced concrete specifications. The transverse projection length of a single opening Lop is the ratio of the opening length to the total length of the RC wall model L between 0.1 to 1. The height projection length Hop is the ratio of the opening height to the total height H of the RC wall model between 0.1 to 1. The horizontal starting position of a single opening must be determined by the vertical starting position of the single opening. The setting method is to first divide the RC wall into a 3 by 3 grid type and plan it to a normal level. The design is shown in Fig.2. If the opening size is smaller than a single block of 3 by 3 grid, the starting position is its center point to determine the variables X and Y values; if the size of the opening is larger than a single block of the 3 by 3 grid, determine the variables X and values Y by which block covers more area of the 3 by 3 grid.

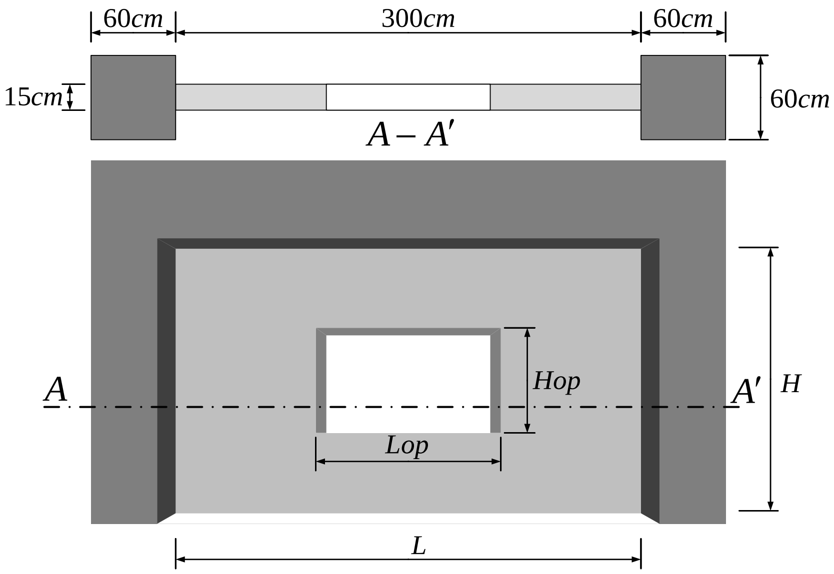


Fig. 1 – schematic diagram of shearing wall opening model

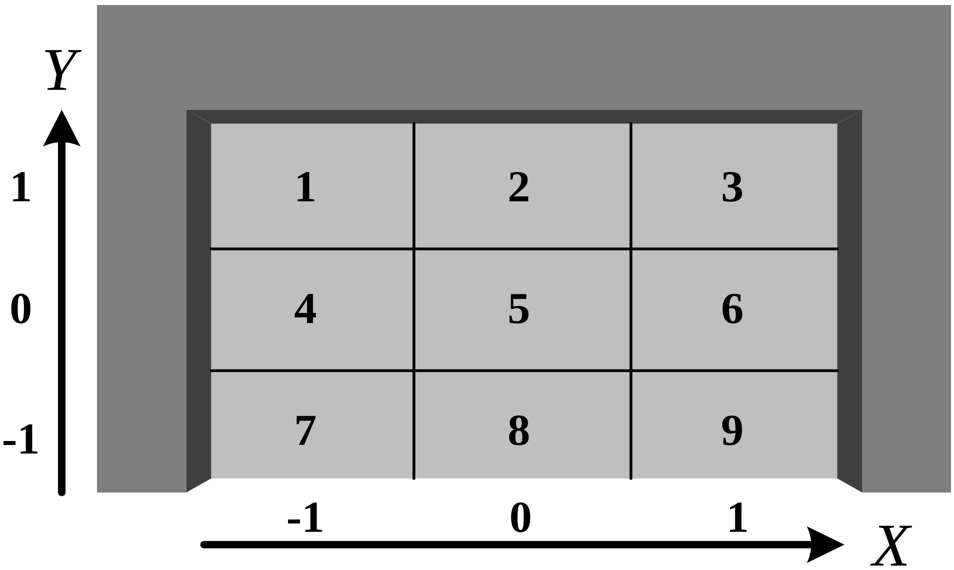


Fig. 2 – schematic diagram of the opening starting position

Table 1 – Regularization of design parameters comparison table

Three level of formalization			
Design parameters	-1	0	1
H / L	0.5	1.25	2
f_c' / f_y	0.0333	0.09165	0.15
ρ_{wall}	0.002	0.00225	0.0025
Lop / L	0.1	0.55	1
Hop / H	0.1	0.55	1
X	-1	0	1
Y	-1	0	1

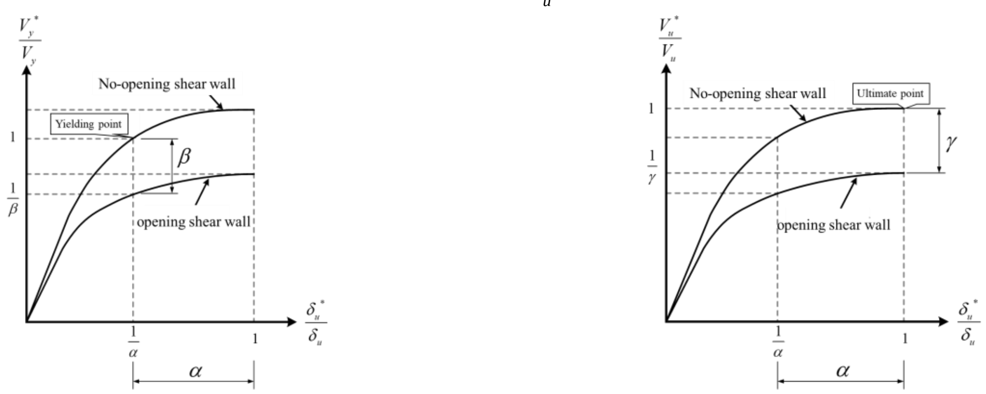
3.2 Shear force and horizontal displacement reduction coefficient of opening RC wall

Because different opening positions and material parameters of the RC wall have different effects on the shear strength of the RC wall, ANSYS finite element software is used to analyze the experimental points of the no-opening RC wall and the opening RC wall created by the response surface method to obtain the relationship of shear force and displacement. Then use Box-Behnken Design regression method to get three reduction coefficients, which are the RC wall yielding displacement δ_y to the limit displacement δ_u ratio α, the horizontal yielding shear strength ratio β of opening V_y^* to non-opening V_y RC walls, and the horizontal limit shear strength ratio γ of opening V_u^* to non-opening V_u RC wall, and normalize the reduction coefficient, such as Eq. (7) to Eq. (10), where the yielding point is known via bilinearization, the schematic is shown in Fig.3. The reduction coefficient can be obtained by combining the above three response surface functions. The SERCB is used to analyze the shear force-displacement relationship of the diagonal brace of a no-opening RC wall and convert it into a horizontal direction. The shear-displacement relationship of the wall can eliminate complicated structure analysis and improve work efficiency without losing accuracy.

$$\alpha = \frac{\delta_y}{\delta_u} \tag{8}$$

$$\beta = \frac{V_y^*}{V_y} \tag{9}$$

$$\gamma = \frac{V_u^*}{V_u} \tag{10}$$



(a) The yield point of shear force (b) The ultimate point of shear force

Fig. 3 – schematic diagram of the reduction factor

4. Establish the response surface function of the opening RC wall

4.1 Experimental design

In this study, based on the parameter design, the Box-Behnken experimental design was used. A total of 62 sets of experimental points was applied as input for finite element analysis. The shear force-displacement relationship of the opening RC wall was obtained through ANSYS finite element analysis. The ratios of yielding displacement-limit displacement α, yielding shear force β and limit shear force γ are used as input values, where the material parameter x_1 is the height-width ratio of a reinforced concrete wall H/L, x_2 is the ratio of the compressive strength of the concrete to the yielding strength of the rebar $f_c^{'}/f_y$, x_3 is the volume ratio of the reinforcement from the reinforced concrete wall ρ, x_4 is the lateral projection length of a single opening wall to the total length of the wall Lop/L, x_5 is the ratio of a single opening transverse height to the total height of the wall Hop/H, x_6 is the horizontal starting position X of a single opening, and x_7 is the vertical starting position Y of a single opening. The analysis results are shown in Table 2.

Table 2 – Parameter design and finite element analysis results

NO.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	α	β	γ
1	0	0	-1	-1	0	0	-1	0.65100	0.76222	0.76060
2	1	-1	0	-1	0	0	0	0.73334	0.61147	0.54197
3	0	0	0	-1	-1	-1	0	0.62570	0.88891	0.91440
4	-1	0	0	0	0	-1	1	0.45031	0.53964	0.58812
5	0	1	0	0	-1	0	1	0.62016	0.72976	0.71417
⋮										
58	0	0	0	0	0	0	0	0.52190	0.38346	0.39749
59	0	0	0	0	0	0	0	0.52190	0.38346	0.39749
60	0	-1	0	0	-1	0	-1	0.72940	0.74676	0.71293
61	0	1	0	0	-1	0	-1	0.54514	0.76438	0.79728
62	0	1	-1	0	0	1	0	0.57826	0.29538	0.30402

4.2 Response surface function selection

This study assumes that the second-order polynomial model replaces of the finite element model with three different reduction coefficients (α 、β 、γ). Therefore, the response surface function should also have three second-order polynomial models ($f_1(x_i)$, $f_2(x_i)$ and $f_3(x_i)$) to approximate real system.

$$
\begin{aligned}
f_i(x_i) = {} & a_0 + a_1(H/L) + a_2(f_c^{'}/f_y) + a_3(\rho_{wall}) + a_4(Lop/L) + a_5(Hop/H) + a_6(X) \\
& + a_7(Y) + a_8(H/L)^2 + a_9(f_c^{'}/f_y)^2 + a_{10}(\rho_{wall})^2 + a_{11}(Lop/L)^2 + a_{12}(Hop/H)^2 \\
& + a_{13}(X)^2 + a_{14}(Y)^2 + a_{15}(H/L)(f_c^{'}/f_y) + a_{16}(H/L)(\rho_{wall}) \\
& + a_{17}(H/L)(Lop/L) + a_{18}(H/L)(Hop/H) + a_{19}(H/L)(X) + a_{20}(H/L)(Y) \\
& + a_{21}(f_c^{'}/f_y)(\rho_{wall}) + a_{22}(f_c^{'}/f_y)(Lop/L) + a_{23}(f_c^{'}/f_y)(Hop/H) \\
& + a_{24}(f_c^{'}/f_y)(X) + a_{25}(f_c^{'}/f_y)(Y) + a_{26}(\rho_{wall})(Lop/L) + a_{27}(\rho_{wall})(Hop/H) \\
& + a_{28}(\rho_{wall})(X) + a_{29}(\rho_{wall})(Y) + a_{30}(Lop/L)(Hop/H) + a_{31}(Lop/L)(X) \\
& + a_{32}(Lop/L)(Y) + a_{33}(Hop/H)(X) + a_{34}(Hop/H)(Y) + a_{35}(X)(Y)
\end{aligned}
\tag{11}
$$

4.3 Response surface inspection and parameter significance verification

Given that the experimental design uses Box-Behnken design for a total of 62 experimental points, the undetermined coefficient cannot exceed 62 unknowns and the reduction coefficients α 、β 、γ are fitting with second-order polynomials which have 36 undetermined coefficients. The accuracy inspections of the response surface functions are 0.8324, 0.9268, and 0.9266, respectively. The results show that the response surface fitted in this research is sufficient to represent the analysis results of the finite element model. The regression fitting equations are shown in Eq. (11), and the polynomial coefficients are shown in Table 3.

Table 3 – α 、β 、γ fitting polynomial

Items	$f_1(x_i)$ Coefficient	$f_2(x_i)$ Coefficient	$f_3(x_i)$ Coefficient	Items	$f_1(x_i)$ Coefficient	$f_2(x_i)$ Coefficient	$f_3(x_i)$ Coefficient
a_0	5.219047E-01	3.834632E-01	3.974881E-01	a_{18}	-4.054762E-02	-2.251641E-02	-5.766989E-03
a_1	2.121658E-02	-8.455073E-02	-8.939898E-02	a_{19}	8.099479E-03	3.113352E-02	3.209110E-02
a_2	-1.057428E-03	-8.541248E-03	-4.311835E-03	a_{20}	-1.448321E-03	-4.787698E-03	-2.358183E-03
a_3	-2.949066E-02	-1.691648E-02	-1.342891E-02	a_{21}	2.886046E-02	-3.257315E-02	-5.185942E-02
a_4	-1.289602E-02	-3.097784E-01	-3.087393E-01	a_{22}	7.290613E-02	1.381629E-02	3.023476E-03
a_5	-1.152716E-02	-1.135808E-01	-1.167873E-01	a_{23}	-3.461299E-02	-1.018941E-02	-4.517104E-03
a_6	1.125021E-02	-9.522640E-03	-1.329910E-02	a_{24}	6.290478E-02	1.659302E-02	-4.384766E-03
a_7	-9.364737E-04	-1.872319E-03	2.130960E-03	a_{25}	5.502138E-02	3.505601E-03	-5.364569E-03
a_8	2.154544E-03	5.599194E-02	5.773983E-02	a_{26}	-7.592772E-03	-7.203837E-02	-6.213656E-02
a_9	3.146908E-02	-4.771841E-03	-1.164582E-02	a_{27}	-4.932694E-02	-5.946442E-03	9.491302E-04
a_{10}	-4.884433E-03	-8.446646E-03	-6.392467E-03	a_{28}	-3.835366E-02	-9.996580E-03	1.535343E-03
a_{11}	3.477597E-02	7.805420E-03	-7.193909E-03	a_{29}	-9.548835E-03	2.828338E-02	3.407998E-02
a_{12}	3.241988E-02	7.342776E-02	6.868476E-02	a_{30}	3.970033E-03	4.462670E-03	8.165529E-03
a_{13}	-7.189925E-03	-1.156860E-02	-3.923321E-03	a_{31}	-9.530941E-03	7.138384E-03	2.776124E-03
a_{14}	1.227530E-02	5.398125E-02	5.081989E-02	a_{32}	1.441945E-02	-7.732271E-03	-6.797419E-03
a_{15}	-4.058639E-02	2.292861E-02	3.433972E-02	a_{33}	4.415137E-02	2.524802E-02	1.639163E-02
a_{16}	-1.807479E-02	-5.791025E-02	-5.287514E-02	a_{34}	1.184477E-02	2.311059E-02	2.665701E-02
a_{17}	8.360356E-05	1.991001E-02	1.647210E-02	a_{35}	-4.054762E-02	-2.251641E-02	-5.766989E-03

Note： $-1 \le x_i \le 1$

5. Analysis and comparison of opening RC wall

5.1 Comparison of different opening positions of opening RC wall

Because the shear strength reduction coefficient of the RC wall proposed by the Japanese code is not considered the same opening size with different position, which the shear strength could be different. In order to explore the mutual influence, the example RC wall modal with the geometric dimensions as $300cm \times 150cm \times 15cm$, the compressive strength f_c' is $280kgf/cm^2$, the yielding strength f_y of the reinforcement is $3055kgf/cm^2$, the reinforcement volume ratio ρ is 0.00225, and the opening size is $165cm \times 82.5cm$. The reduction coefficient calculated through the response surface function, as shown in Table 4. The results are applied to the SERCB program and compared with the ANSYS analysis results. After normalization, the accuracy of the non-opening RC wall is discussed first and then the opening position is selected. Refer to Fig.2, select opening position 1, position 3, position 5, position 7, and position 9 respectively as a basis for comparison. The analysis comparison result are shown in Fig.4 to Fig.11.

Table 4 – Reduction factor of open RC wall in different positions

Reduction factor	Opening position-1	Opening position -3	Opening position -5	Opening position -7	Opening position -9
α	0.4503	0.5456	0.4865	0.4994	0.5672
β	0.5396	0.6255	0.5566	0.6173	0.5912
γ	0.5881	0.6333	0.5777	0.6462	0.5893

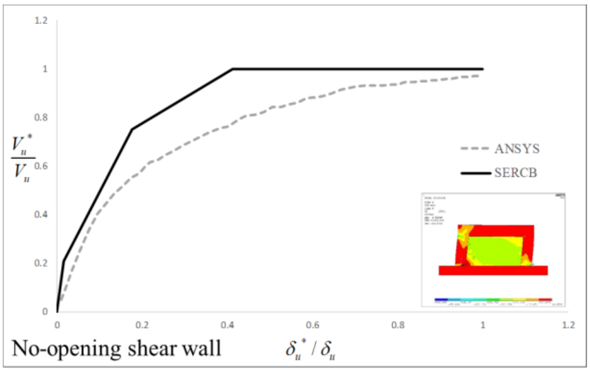


Fig. 4 – Analysis and comparison results of regularization of non-opening walls

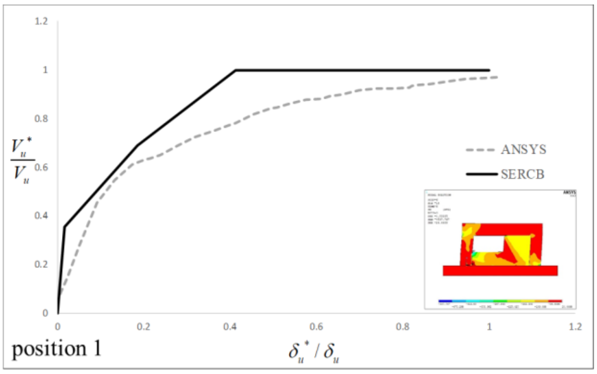


Fig. 5 – Analysis and comparison results of the opening wall normalized at position 5

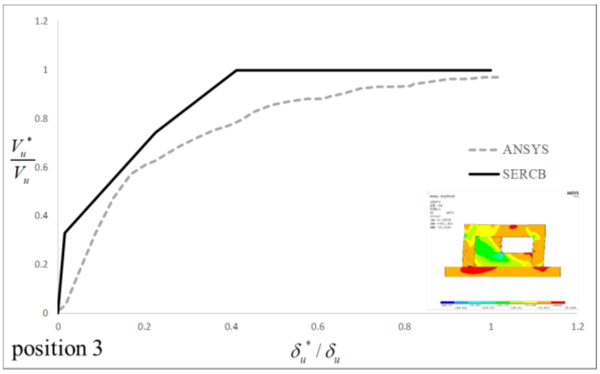


Fig. 6 – Analysis and comparison results of the opening wall normalized at position 1

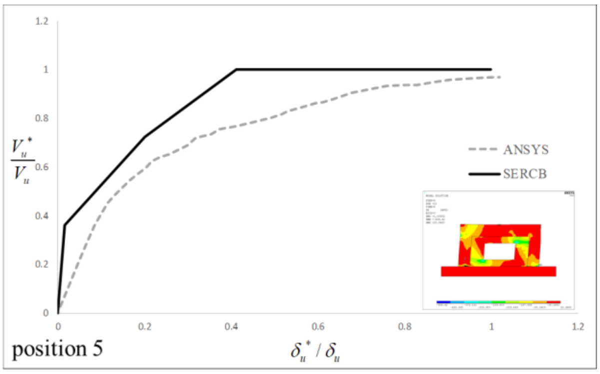


Fig. 7 – Analysis and comparison results of the opening wall normalized at position 7

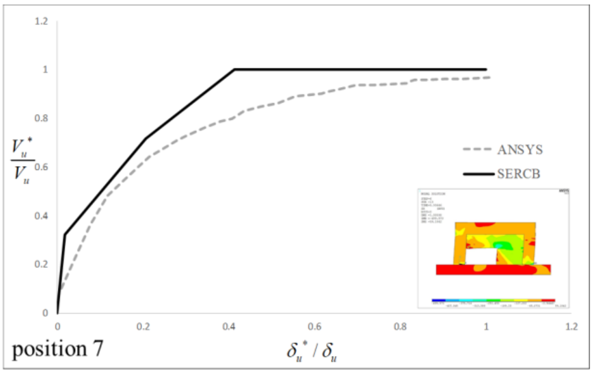


Fig. 8 – Analysis and comparison results of the opening wall normalized at position 3

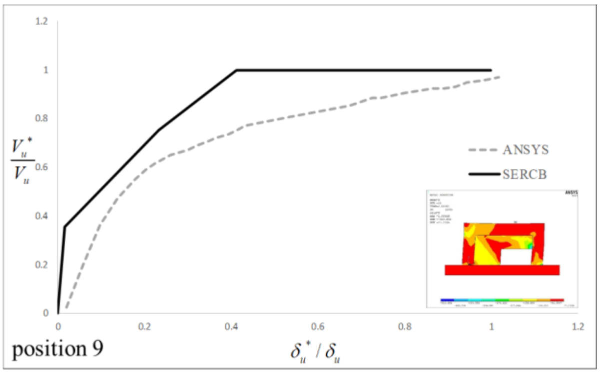


Fig. 9 – Analysis and comparison results of the opening wall normalized at position 9

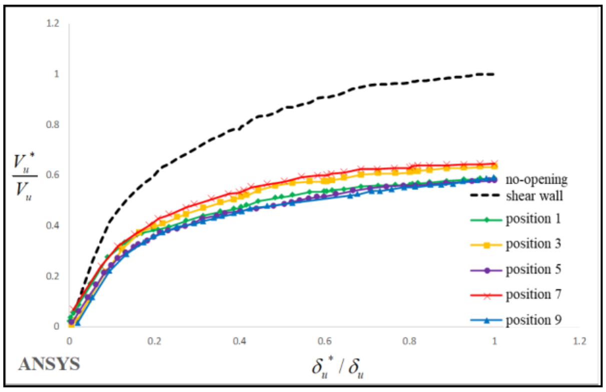


Fig. 10 – ANSYS analysis results comparison

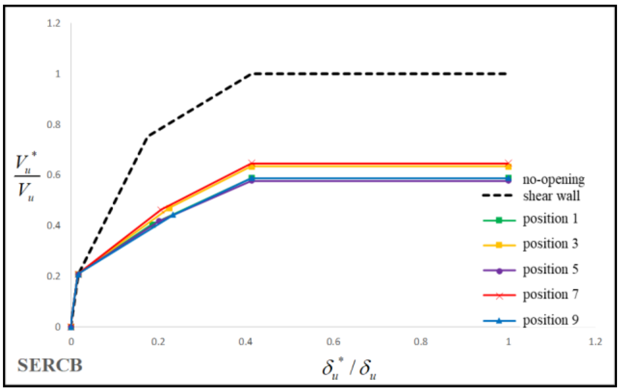


Fig. 11 – SERCB analysis results comparison

5.2 Verification of experimental data and analysis results of opening RC wall

In this study, Hwang et al. [8] performed five sets of opening RC wall experiments in 2001. One group of the specimens were non-opening RC walls, and the rest were opening RC walls. However, the specimens are all 300 cm wide, 195 cm high, 12 cm thick, the compressive strength f_c' of the concrete is between 193 to 226 kgf/cm^2, the yielding strength of the rebar is $3940 kgf/cm^2$, and the opening size is shown in Table 5.

Analyze the shear strength without opening through the SERCB program, and calculate the shear strength of the opening wall through the reduction coefficient (α, β, γ), the reduction coefficient is shown in Table 6. The wall strength calculations by SERCB, ANSYS and Japan's code are compared, as shown in Fig.12 to Fig.16. Although the initial stiffness of the analysis results is higher than the initial stiffness of the experiment, the shear strength of the analysis results is closer to the experimental data than the Japanese code, which can indicate that the reduction coefficient of the response surface function proposed by this research has a more accurate result.

Table 5 – Experimental data of open RC wall by Hwang Shyh-Jiann et al.

No.	$L_{(cm)}$	$H_{(cm)}$	$b_{w(cm)}$	$f_c'\left(kgf/cm^2\right)$	$f_y\left(kgf/cm^2\right)$	$Lop_{(cm)}$	$Hop_{(cm)}$
BMNFLWRC	350	195	12	193	3940		
NFLW01W	350	195	12	202	3940	250	60
NFLW01WF	350	195	12	200	3940	190	60
NFLW01D	350	195	12	226	3940	60	170
NFLW01DF	350	195	10	201	3940	60	120

Table 6 – Reduction coefficient of an open RC wall of experiment

Reduction coefficient	NFLW01W	NFLW01WF	NFLW01D	NFLW01DF
α	0.590215	0.549247	0.463672	0.529693
β	0.389283	0.551343	0.629257	0.778173
γ	0.386734	0.557232	0.634037	0.761313

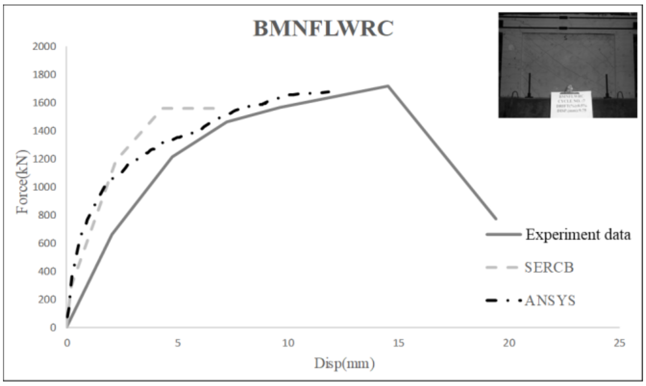


Fig. 12 –BMNFLWRC Test Experiment and Analysis Comparison

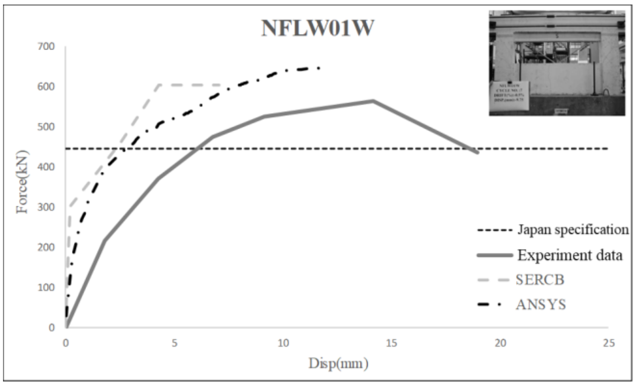


Fig. 13 – NFLW01W Test Experiment and Analysis Comparison

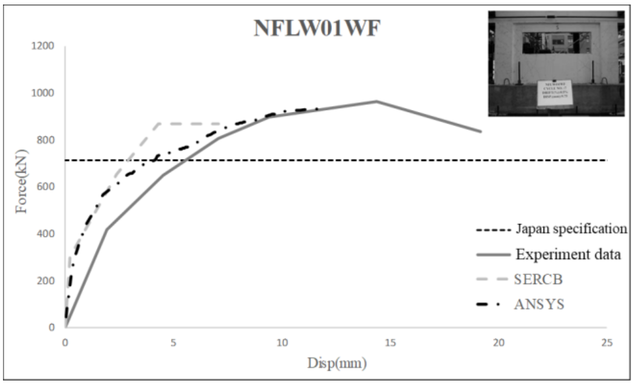


Fig. 14 – NFLW01WF Test Experiment and Analysis Comparison

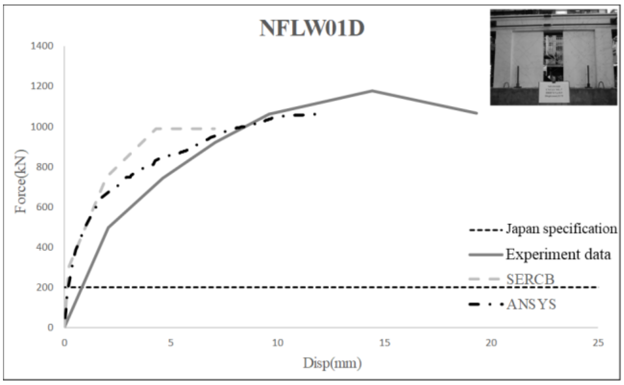


Fig. 15 – NFLW01D Test Experiment and Analysis Comparison

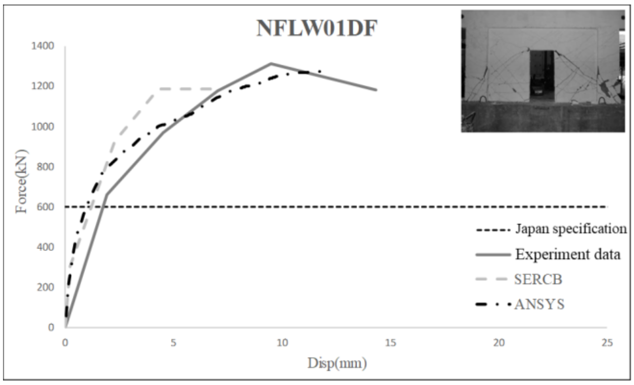


Fig. 16 – NFLW01DF Test Experiment and Analysis Comparison

6. Concluding remarks

In this article, the following conclusions are put forward through the analysis process and results of the test sample:

1. Using finite element software to analyze the opening RC wall is more time-consuming than the no-opening RC wall. Due to the different positions of the openings, it is necessary to remodel. Besides, the modal need to adjust the convergence of the mesh caused by the different number and opening location. The stress distribution behavior would affected by the opening positions. It needs to be judged, whether it is reasonable or not. On the other hand, the non-opening RC wall does not need to be remodeled. It only needs to change the parameters of concrete and rebar. The overall mesh convergence speed is fast, and the stress distribution behavior is diagonal cracking. Therefore, the shear force-displacement

relationship of opening RC wall can be quickly obtained by establish the response surface function and analyze shear force-displacement of the no-opening RC wall.

2. After using the finite element analysis to obtain the shear force-displacement relationship between the opening RC wall and the no-opening RC wall, three reduction coefficient are acquired by the response surface method, which are horizontal displacement α, the shear force at the yielding point β and the limit shear point γ. The shear force-displacement relationship of opening RC wall can be obtained by the no-opening RC wall with reduction coefficients.
3. It is obtained from the analysis results of different opening positions that when the shear strength of the opening in the diagonal direction is the lowest in both ANSYS and the reduction factor γ analysis, it is a reasonable phenomenon. The reduction coefficient proposed by this research is applied to different opening positions, and the calculated shear strength is convincing, which can improve the shortcomings of the Japanese code that cannot consider the opening position.
4. From the experimental data of Hwang et al. and SERCB analysis with reduction coefficients, it is found that the error of the shear strength is quite small, and the calculated shear strength comparing to Japanese standards is closer to the experimental results. The calculation result of the limit strength reduction coefficient γ can predict the value of opening RC wall shear strength and has reference value.
5. At present, Taiwan has no relevant specifications for the design of the opening RC wall. Although many experts have provided insights and related experimental studies, there is no uniform approach. This paper proposes a finite element model analysis based on the response surface method, with the aim of improving work efficiency without losing accuracy. Through statistics and the number of input groups of related parameters of finite element analysis provided by opening and no-opening RC walls, the finite element analysis obtains the shear force-displacement ratio output data. The appropriate response surface function is used to replace the finite element model with the input and output relationship. In the future, the shear force-displacement data can be obtained in the SERCB program by inputting the parameters of the no-opening wall, then use the reduction coefficient to predicts the relationship of shear force-displacement of an opening RC wall.

6. References

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