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SWESA - Optimization in the design of shear walls

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ABSTRACT

Shear walls are commonly used in tall buildings to resist the effects of gravity loads and story shears due to lateral loads. They are deep, relatively thin, vertically cantilevered reinforced concrete members. Together, shear walls and frames provide the overall strength to withstand wind or earthquake forces in tall buildings. A software, SWESA (Shear Walls Expert Systems Analysis), is developed to incorporate the expertise from a variety of designs on shear walls. Wind pressures are calculated and distributed over the height of the building in accordance with specific design provisions. Story shears and overturning moments are determined analytically. The program ensures that the lateral deflection calculated from the application of wind forces does not exceed the required deflection index. A simple optimization technique is utilized to obtain the optimal thickness of shear walls in order to satisfy the allowable drift requirement. The strength of shear walls containing uniformly distributed vertical reinforcement and subjected to combined axial load, bending moment and shear force can be calculated in the developed program. Strength of lintel beams due to the effect of openings in shear walls can be calculated.

INTRODUCTION

Shear walls are the subject of numerous research topics in the literature. An investigation for framed shear wall behavior using neural networks (Mo and Lin 1994) concluded the applicability of the preditction capabilities of neural networks. Specimens were tested to investigate the effect of small openings on the strengh and stiffness of shear walls in reactor buildings (Kobayashi *et al.* 1995). The specimens were subjected to reversed cyclic loads. It was conculuded that scattered small openings in shear walls scarcely affect the wall strength. However, the openings do affect the strength if they are located closely to each other. Other investigators used Framework Method (FWM) in the elastic-static analysis of shear wall/slab systems in multi-story buildings (Cocchi 1995). The prediction of the capacities and failure modes of reinforced concrete walls was studied (Uehara 1996). The research dealt with the yield criteria of the reinforced concrete shear plane when subjected to moment, shear and axial load. The yield criterion was obtained by adding the yield criteria of concrete and reinforcing bars (American Concrete Institute 1995).

In the early 1960s John McCarthy at MIT invented the first artifical intelligence programming language - Lisp (Taylor 1988). Since then, researchers have devoted efforts to develop new techniques that can more easily encode rules of engineering practice in computers. Since the beginning of the eighties, when personal computers became readily available and accessible to more people, articicial intelligence research has had profound effects on engineering practice, particularly in the civil engineering area (Adeli 1988, Maher 1987). Owing to the growing demand, by design offices for example, for a practical design tool for shear walls, a computer code is needed to implement systematic design procedures in an artificial intelligence environment. The primary concerns of the program developed by the authors and presented in this paper are:

1. Fast executing path,
2. Professional information and valuable expertise,
3. Economical benefit,
4. Interaction and compatibility with other softwares.

Initially Turbo Prolog (Borland International 1988), an IBM version, was adopted mainly due to economical consideration in comparison with other logic programming languages. Using Turbo Prolog, special purpose softwares for structural engineering can be developed in a matter of days. The interface capabilities make the exchange of information between software and displaying graphics quite easy. However, Turbo Prolog can be quite tedious and confusing in developing complex expert systems. For such systems it is more advantageous to use expert system development shells such as Crystal (Intelligent Environments, Inc. 1994) to affect rapid development of a wide range of expert system applications. The only drawback of such development products is that the purchasing cost is quite high. Nowadays, Microsoft Visual Basic can be easily linked to the developed codes (Microsoft 1998).

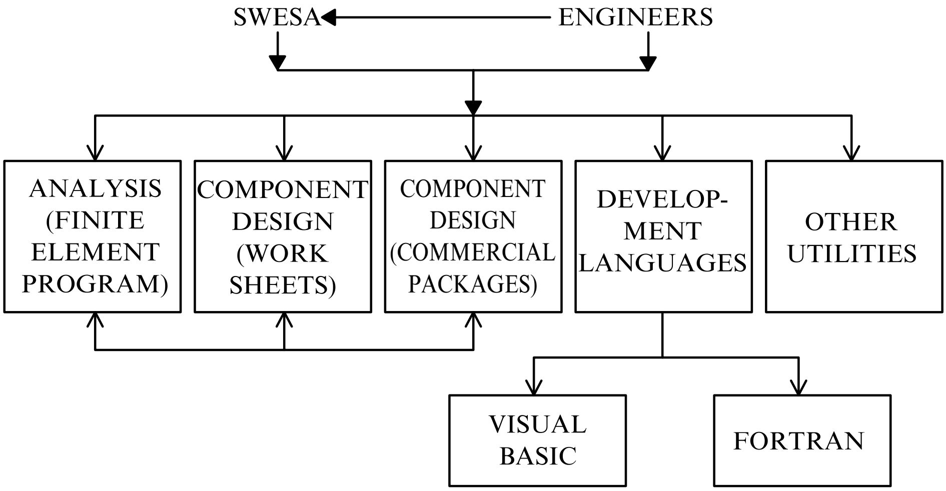
In general, the developed program, SWESA (Shear Walls Expert Systems Analysis), acquires information by raising queries to the end user at each stage. The applied wind forces are determined and distributed along the height of the shear walls. Story shears and overturning moments are then calculated in accordance with the applied wind forces. Lateral displacements are computed by an analytical approach (Coull and Chaudhury 1967). An optimization technique, optimality criterion method (Lev 1981, Jan 1987) is utilized to determine the optimal thicness of shear walls. Finally, strength checks of lintel beams (Maclead 1970, Coull and Chaudhury 1967, Chan and Kuang 1989) and design of vertical reinforcment of shear walls (Cardenas *et al,* 1973) are performed according to specific provisions of the 1995 ACI Code (American

Concrete Institute 1995). While designing shear walls it is necessary to consider their effective strengths against flexure, shear and axial load. The effect of openings plays an important role in shear walls. Accordingly, the use of this systematic procedure is adequate for practical design. SWESA should run interactively, and best of all, intelligently. A systematic scheme which highlights each specification used in finding the solution helps the end user in following the step by step approach. The purpose of SWESA is to serve as an intelligent knowledge base for retrieving, editing, and inferring designs of shear walls.

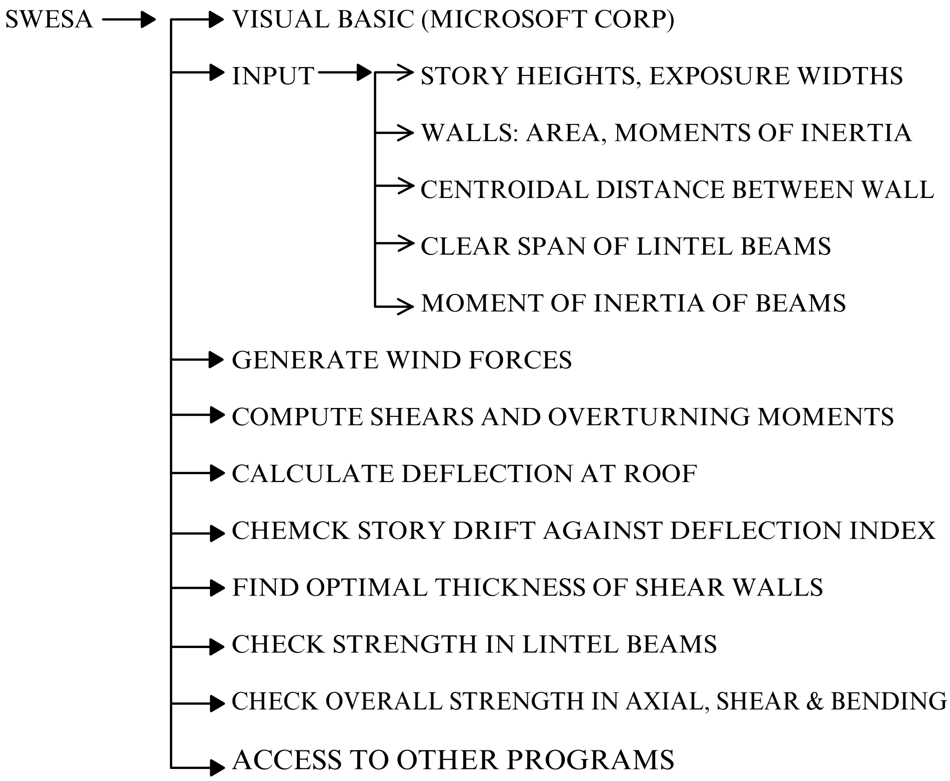
INTERACTION OF SWESA WITH OTHER SOFTWARES

It is essential to consider the interaction and compatibility of SWESA with other softwares. Traditionally, it is impossible to prepare Fortan programs and have them interface with other existing software. Fortunately, one merit of artificial intelligence programming languages such as Microsoft Visual Basic are their interface capabilities which allows exchange of information between applications and operating systems very easity. A large number of available functions and screen facilities povide an easy, nontechnical way to produce powerful applications. The flow chart below highlights the interaction and compatibility provided in SWESA. It ought to be pointed out that the working of SWESA does not interfere with any existing software. There is also the flexibility to include future incoming packages easily. Experienced engineers can still have access to existing software without getting into SWESA. However, they will not be able to obtain the optimal thickness in designing shear walls. The complicated procedure in designing lintel beams and shear walls will also not be available to them. Therefore, in the authors' opinion, it is advantageous to use SWESA to minimize the difficulties in designing shear walls.

The executing environment of SWESA is incorporated entirely in Visual Basic graphics display mode. Interactively, a sequence of queries are raised in order to obtain data of shear walls under consideration. According to story heights and the corresponding exposure widths, SWESA generates applied wind forces along the height of the building in both directions. Shear forces and overturning moments are calculated accordingly. By the help of an analytical model (Coull and Chaudhury 1967), the lateral deflection at roof level is determined. Instead of the allowable deflection index, an optimality criterion method is used to find the optimal thickness of shear wall. After the requirement in story drift is satisfied, strength of lintel beams is calculated to check their adequacy. Finally, the overall strength in axial, shear and bending modes of deformation of the shear walls is calculated for design purposes. Updating or incorporation of new information can be performed easily. Thus, professional information and valuable expertise are shareable in SWESA.



The primary role of SWESA is to help an experienced engineer in designing shear walls. Its internal scheme of reasoning is illustrated as follows:



CALCULAION OF OPTIMAL THICKNESS

As mentioned above, the approach adopted herein for finding the optimal thickness t^* is based on an optimality criterion method (Lev 1981, Jan 1987). The scheme itself is robust. The objective of the optimization is the minimization of the structural weight which reflects the minimum cost in materials. The constraints are the flexural strength and the lateral deflection of the shear walls. Some of the formulations are discussed briefly in this section. For shear walls having different cross sections along their heights, such as illustrated in Fig. 1, the lateral deflection at the roof, Δ, can be determined analytically as follows (Lev 1981):

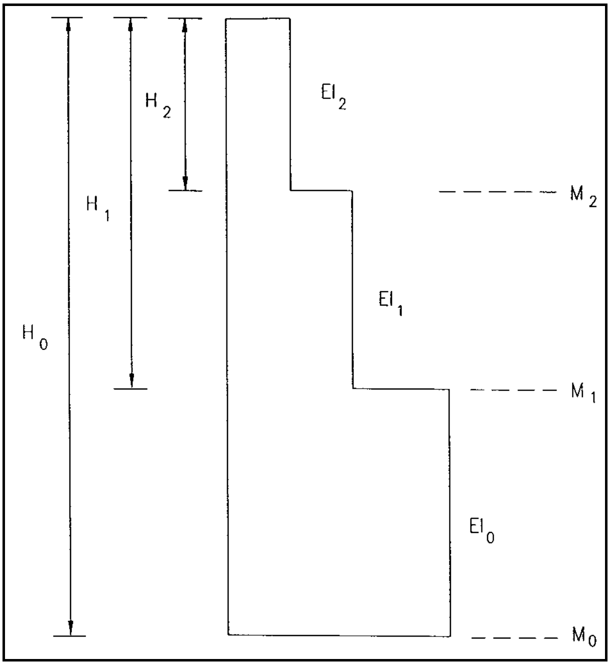


Figure 1. Shear walls of different cross sections.

$$\Delta = \frac{M_0\, H_0^2}{4EI_0} + \frac{M_1 H_1^2}{4EI_0}(n_1 - 1) + \frac{M_2 H_2^2}{4EI_0}(n_2 - n_1) + \ldots.. \qquad (1)$$

where E = Young's modulus of concrete; H_0 , H_1 , H_2 = the distances from ground floor, 2nd and 3rd differentia to the roof respectively, I_0 , I_1 , I_2 = the moments of inertia of wall at the ground floor, 2nd and 3rd differentia respectively; M_0 , M_1 , M_2 = the overturning moment at the ground floor, 2nd and 3rd differentia respectively; and n_1 = ratio I_0 / I_1 , n_2 = ratio I_0 / I_2 .

Choosing the total weight W as the objective function to be optimized, the optimization criteria can be stated in the following manner:

Minimize $W = \rho A_0 \ (H_0 - H_1) + \rho A_1 (H_1 - H_2) \ + \ \rho A_2 \ (H_2 - ...) + ...$ (2)

Subject to

$$\Delta \ \leq \ \overline{\Delta} \tag{3}$$

in which ρ is the density of the shear walls; $\overline{\Delta}$ is the required deflection index; A_0, A_1, A_2 = the cross-sectional areas of the wall at the ground floor, 2nd and 3rd differentia respectively.

The Lagrangian required prior to forming the Kuhn-Tucker conditions (Luenberger 1989) is expressed as:

$$L \ (\lambda, A_0, A_1, A_2, ...) = \lambda(\Delta - \overline{\Delta}) + \rho A_0(H_0 - H_1) + \rho A_1(H_1 - H_2) + \rho A_2(H_2 - ...) + ... \tag{4}$$

where λ is a Lagrange multiplier. At the optimum, the Kuhn-Tucher conditions become:

$$\Delta - \overline{\Delta} = 0 \tag{5}$$

$$\frac{\partial \Delta}{\partial A_0} + \rho \ (H_0 - H_1) = 0 \tag{6}$$

$$\frac{\partial \Delta}{\partial A_1} + \rho \ (H_1 - H_2) = 0 \tag{7}$$

$$\frac{\partial \Delta}{\partial A_2} + \rho \ (H_2 - ....) = 0 \tag{8}$$

and

$$\lambda \ (\Delta - \overline{\Delta}) = 0 \tag{9}$$

$$\lambda \ \geq \ 0 \tag{10}$$

$$(\Delta - \overline{\Delta}) \ \leq \ 0 \tag{11}$$

Equations 9 through 11 are the necessary conditions for an optimum.

By using the relationship derived from equations (5) to (11) and assuming the ratios n_1 , n_2... are constants, the moment of inertia at the ground floor I_0 near the optimum can be determined using the following expression:

$$I_0 \ = \left[\frac{M_0 H_0^2}{4E} + \frac{M_1 H_1^2}{4E} \ (n_1 - 1) \ + \ \frac{M_2 H_2^2}{4E} \ (n_2 - n_!) + ...\right] \Big/ \ \overline{\Delta} \tag{12}$$

The cracking moment I_{cr} can be computed from the *ACI* (American Concrete Institute 1995). Thus, the optimal thickness t^* of a shear wall for a rectangular cross section at the ground floor is:

$$t^* = 12 \ I_0 / L_0^3 \tag{13}$$

Where L_0 is the cross-sectional length of the shear walls at the ground floor. Similarly, optimal thickness at 2nd and 3rd differentia can be derived by equations

(6) and (7). More accurate results in optimal thickness at ground floor. Similarly, optimal thickness at 2nd and 3rd differentia can be derived by equations (6) and (7). More accurate results in optimal thickness at ground floor and at other cross sections of the shear walls can be derived by taking into account the ratios n_1, n_2, ... It should be mentioned here that an "optimum has to satisfy constraints such as drift (lateral deflection), strength (axial, shear, flexure and torsion). The optimal solution provides the variable thicknesses throughout the height of the building. This may lead to different optimum thickness than the initial input/ uniform constant thickness. Nevertheless, equation (13) provides a rapid estimation in the optimal thickness of the shear wall. This can be achieved because SWESA starts with a unique initial wall thickness. By using the optimization techniques the most feasible wall thickness can be found for each level. More information will be provided later in the practical application section.

DESIGN CONSIDERATIONS

For years, structural engineers have observed that rigid framing systems bend predominantly in a shear mode, and shear wall systems deflect predominantly in a bending mode, i.e. as a cantilever (MacLeod 1970). The difference in such behaviors under wind load, in combination with the in-plane rigidity of the floor slabs, causes nonuniform interacting forces to develop when shear walls and frames are both present. Therefore, suggested procedures for wind analysis of high-rise buildings have been proposed constantly throughout the literature (MacLeod, 1970, Coull and Choudhury, 1967; Chan and Kuang, 1989). A special precaution is taken in the opening area of the shear walls.

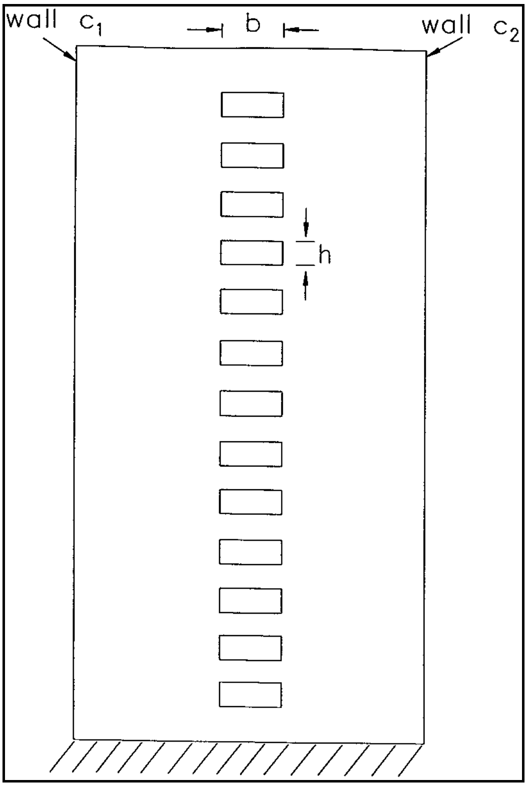


Figure 2. Shear walls with opening.

As shown in Fig. 2 the effect of the openings on the stiffness of the shear walls is determined by the parameters, α, μ, and K_4, expressed as follows (Lev 1981):

$$\alpha = \sqrt{\frac{12I_b}{hb^3}\left[\frac{\ell^2}{I_{c1}+I_{c2}} + \frac{(A_{c1}+A_{c2})}{A_{c1}\ A_2}\right]} \tag{14}$$

$$K_4 = 1 - \frac{3}{\mu}\left[\frac{1}{3} + \frac{\sin h\ (\alpha\ H)}{(\alpha H)^3\ \cos h\ (\alpha H)} - \frac{1}{(\alpha H)^2}\right] \tag{15}$$

and

$$\mu = 1 + \frac{(A_{c1}+A_{c2})(I_{c1}+I_{c2})}{A_{c1}\ A_{c2}\ b^2} \tag{16}$$

where A_{c1}, A_{c2} = the cross-sectional areas of the shear walls $c1$ and $c2$; I_{c1}, I_{c2} = the moments of inertia of the shear walls $c1$ and $c2$; h = story height; H = the total height of the wall; b = the clear span of lintel beams; ℓ = the distance between the centroidal axes of the wall sections; I_b = the moment of inertia of a connecting beam.

ACI 318-95 (American Concrete Institute, 1995) allows the design of walls for flexure and axial loads like columns, but with certain limitations and exceptions. For designing walls, an empirical method can be used. There are also special provisions in ACI for designing walls against shear. The ACI formulae for design of walls against axial, flexure, and shear are implemented in SWESA.

PRACTICAL APPLICATION

A practical application of SWESA is illustrated in order to show the effectiveness in designing high-rise buildings. An apartment building, as shown in Fig. 3, is analyzed for wind loads along its wide and narrow exposures. The proposed building is 434.6 ft high, 124 ft wide in one direction, and 86 ft wide in the other direction. Initially, the moments of inertia I_0 = 18,000 ft^4 in the x-direction, and I_0 = 23,000 ft^4 in the y-direction, n_1 = 1.3, n_2 = 1.8; H_0 = 434.6 ft, H_1 = 318.3 ft, H_2 = 168.3 ft. The target deflection index in 0.84 ft at the top.

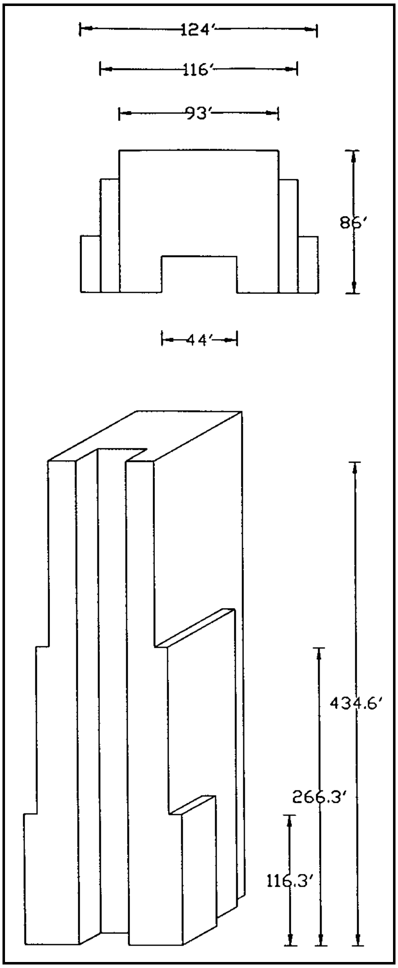


Figure 3. Plan view and elevation view of the illustrated example.

The results obtained from SWESA are shown in Table 1. It provides a tool for selecting adequate material and cross sectional properties. The final selection of I_o = 25,000 ft^4 (29,100 ft^4 in the y-direction) for f_c' = 6,000 psi, I_1 = 20,500 ft^4 (24,300 ft^4 in the y-direction) for f_c' = 5,000 psi, and I_2 = 17,000 ft^4 (20,000 ft^4 in the y-direction) for f_c' = 4,000 psi is based on the solution of SWESA. The calculated deflections at the roof in the x and the y directions are 0.84′ and 0.53′ respectively. Appendix C lists the input and output parameters used in the illustrative example.

Table 1. Results Obtained from SWESA (Illustrative Example)

Design Parameter	Initial Data x-Dir./y-Dir.	SWESA Solution
I_0 (ft^4)	18000/23000	30300/45000
I_1 (ft^4)	14000/18000	23600/35000
I_2 (ft^4)	10000/13000	17000/25000
M_0 (k-ft)	254000/178000	--
M_1 (k-ft)	174000/122000	--
M_2 (k-ft)	267000/397000	--
Δ (ft)	0.85/0.46	0.84/0.6
Thickness	8*	12*

An "optimum" has to satisfy constraints such as drifts (lateral deflections) and strengths (axial, shear flexure and torsion). The example starts with an initial thickness of 8 inches. Apparently, the 8 inch thick shear wall, even though it is lighter in weight, does not meet the constraints' requirements. Initially, the shear wall is unsafe with the 8 inch thickness. In addition, the optimal solution gives variable thickness along the height of the tall buildings. The 12 inch thickness is the shear wall thickness at the first floor level. It is different than the initial input of the uniform/constant thickness.

A typical model of shear walls can be calculated with any finite element software. However, the elastic modulus of reinforced concrete can only be approximated by formulae from the ACI code. It is conservative to do so. As mentioned earlier, SWESA will start with one unique initial wall thickness and optimally find the most feasible wall thickness for each level of the building. Such results can not be achieved using any commercial package. The reason is that the only way to achieve that using commerical packages is by trial and error. It is almost impossible to do so manually to find the most feasible wall thickness for each level of the building. This is the advantage of SWESA, which adopt the optimization technique. To the best of the authors' knowledge, no software with such capabilities and flexibilities exists commercially to verify the results obtained by SWESA.

CONCLUSIONS

A software, SWESA, for designing shear walls is introduced. Theoretical formulations and important design considerations of shear walls, along with an optimality criterion method to find the optimal thickness are presented. The effectiveness of lintel beams near the openings of shear walls is also considered. Finally, a practical design example is presented to illustrate the software's adequacy.

In general, this computerized automation system adopts state-of-the-art knowledge in the design of shear walls. The primary advantage. of SWESA is achieved by the retrieval of valuable expertise in an economical manner. The final design provides adequate strength to withstand axial loads, flexure and shear.

ACKNOWLEDGEMENTS

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APPENDIX A - UNITS CONVERSION FACTORS

To convert	To	Multiply by
inch (in.)	millimeter (mm)	25.4
feet (ft)	millimeter (mm)	305
pound force (LbF)	Newton (N)	4.45
kip	kilonewton (kN)	4.45
pound force per square inch (psi)	kilopascal (kPa)	6.89
pound force per square foot (psf)	kilopascal (kPa)	0.0478
pound force per cubic foot (pcf)	kilogram/meter (kg/m)	16
ksi	MPa	6.89
ft.kips	N-m	1360

APPENDIX B - NOTATION

The following symbols are used in this paper:

A_0 = cross-sectional area of the wall at the ground floor;

A_1 = cross-sectional area of the wall at the 2nd differentia;

A_2 = cross-sectional area of the wall at the 3rd differentia;

$A_{c1},\ A_{c2}$	=	the cross-sectional area of the shear walls $c1$ and $c2$;
b	=	clear span of lintel beams;
E	=	Young's modulus of shear walls;
f_c'	=	compressive strength of concrete;
h	=	story height;
H	=	total height of the wall;
H_0	=	distance from the ground floor to the roof;
H_1	=	distance from the 2^{nd} differentia to the roof;
H_2	=	distance from the 3^{rd} differentia to the roof;
I_0	=	moment of inertia of the wall at the ground floor;
I_1	=	moment of inertia of the wall at the 2^{nd} differentia;
I_2	=	moment of inertia of the wall at the 3^{rd} differentia;
I_b	=	moment of inertia of a connecting beam;
$I_{c1},\ I_{c2}$	=	the moments of inertia of shear walls $c1$ and $c2$;
K_4	=	shear wall parameter;
ℓ	=	distance between centroidal axes of the wall sections;
L	=	Lagrangian;
L_0	=	cross-sectional length of the wall at the ground floor;
L_1	=	cross-sectional length of the wall at the 2^{nd} differentia;
L_2	=	cross-sectional length of the wall at the 3^{rd} differentia;
M_0	=	overturning moment at the ground floor.

APPENDIX C

1. Input Parameters for Illustrative Example

1. Building name? My building
2. How tall is the building? 434.6
3. What is the elevation @ ground floor? 0
4. What is the wide exposure width @ ground floor? 124
5. What is the narrow exposure width @ ground floor? 86

6. At ground floor the wide exposure width is 124, how high does it reach? 116.3
7. At the elevation of 116.3, what is the exposure width above? 116
8. How high does it reach? 150
9. At the elevation of 266.3, what is the exposure width above? 93
10. How high does it reach? 168.3
11. At ground floor the narrow exposure width is 86, how high does it reach? 116.3
12. What is the exposure width above? 86
13. How high does it reach? 150
14. At the elevation of 266.3, what is the exposure width above? 86
15. How high does it reach? 168.3
16. What is the moment of inertia @ wide exposure? 18,000
17. What is the cross sectional area? 10664
18. What is the specified concrete strength? 6,000
19. How high does it reach? 116.3
20. At the elevation of 116.3, what is the moment of inertia above? 14,000
21. What is the cross sectional area? 9976
22. What is the specified concrete strengh? 5,000
23. How high does it reach? 150
24. At the elevation of 266.3, what is the moment of inertia above? 10.000
25. What is the cross sectional area? 7998
26. What is the specified concrete strength? 4,000
27. How high does it reach? 168.3
28. What is the moment of inertia @ narrow exposure @ ground floor? 23,000
29. How high does it reach? 116.3
30. At the elevation of 116.3, what is the moment of inertia above? 18,000
31. How high does it reach? 150
32. At the elevation of 266.3, what is the moment of inertia above? 13,000
33. How high does it reach? 168.3

II. Output Parameters for Illustrative Example

@ WIDE exposure:

Deflection Index = H/520

Allowable drift @ top (X) = 0.835769

Drift @ top provided = 1.777147

Scaling factor = 2.12636

@ NARROW exposure:

Deflection Index = H/520

Allowable drift @ top = 0.835769

Drift @ top provided (Y) = 0.60110018

Scaling factor = 0.719219

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SWESA – الحل الأمثل في تصميم حوائط القص

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خلاصة

تستخدم حوائط القص في المباني العالية لمقاومة تأثير وزن المبنى وقوى القص في الأدوار نتيجة للأحمال الجانبية وحوائط القص عميقة وقليلة السمك نسبياً كما أنها كابولية عمودياً ومن الخرسانة المسلحة.

إن حوائط القص تعمل مع براويز المبنى لتدعم المبنى ضد قوى الرياح والزلازل في المباني العالية ومقدم في هذا البحث برنامج للحاسب الآلي (SWESA) ليمكن المختصين من إيجاد تصميمات متعددة لحوائط القص ويتم توزيع حمل الرياح على المبنى بناء على مواصفات التصميم كما يتم تحديد قوى القص وعزم الانقلاب والعزوم تحليلياً ويتم كذلك حساب الترخيم الجانبي نتيجة لحمل الرياح بحيث أنه لا يتعدى المؤشر المطلوب للإزاحة كما تستخدم طريقة مبسطة ولكن فعالة لإيجاد السماكة المثلى لحوائط القص بناء على تحقيق الأمان في متطلبات الإزاحة المسموح بها ويتم كذلك حساب قوة الانثناء لحوائط القص ذات الحديد المسلح متساوي التوزيع والمعرض للقوى المحورية والانثناء والقص.

وأخيراً فإن القوة المطلوبة للعتبات نتيجة لتأثير الفتحات في حوائط القص تم اعتبارها.