

# INTEGRATED SEISMIC ANALYSIS AND DESIGN OF SHEAR WALL STRUCTURES

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**Abstract**—This paper summarizes a new approach for the design of concrete shear wall structures for nuclear facilities. Static and dynamic analyses are carried out with the same finite element model, using SAP2000 and SASSI2000 computer programs, respectively. The method imports the dynamic solution from SASSI2000 into the optimum concrete (OPTCON) design computer code in order to compute the stresses in the concrete members for every time step of analysis. Static stresses are imported from the static solution for applicable static loads, and total stresses are computed for concrete design. The design process allows both element-based and cut-section design methods.

This approach has the advantage of considering the stress time history in the design of concrete members, avoiding the conventional approach of combining maximum seismic stresses for all elements simultaneously. Significant savings in concrete design (both time and material) were obtained in a test problem, simulating a typical shear wall structure for nuclear facilities.

**Keywords**—computer code, cut-section design, element-based design, impedance matrix, integrated design, mass matrix, optimum design, reinforcement, seismic design, shear wall structure, shell element, static and dynamic analysis, stiffness matrix

## INTRODUCTION

The current approach to the design of safety-related shear wall structures generally involves using the SASSI2000 [1] computer code for the seismic soil-structure interaction (SSI) analysis. Acceleration profiles obtained from the SASSI analysis are applied to a detailed finite element model as equivalent static loads to determine the seismic forces. The SASSI models may be coarser than the static models. The design may be carried out using a concrete design program, with appropriate combination of applicable static loads. In the design process, maximum seismic forces in each of the three orthogonal directions are combined. This step assumes that all maximum seismic loads are acting at the same time, thus resulting in a very conservative design.

The conventional two-step design procedure described above is tedious and requires two separate analyses to develop design loads and the compatibility of the static and the dynamic models needs to be demonstrated for each application. However, it has the advantage that a detailed static model considering major openings and composite slabs can be analyzed

for design. The proposed approach requires the same model to be used for static and dynamic analysis and thus offers a more robust approach for concrete design, if the same static model can be used in the dynamic analysis.

For dynamic analysis, the new version of the SASSI2000 code is used. This version has the state-of-the-art thin/thick shell element with five stress output points allowing computation of out-of-plane shear forces. To avoid transfer of large sets of stress time histories from SASSI2000 to optimum concrete (OPTCON) [design computer code], the transfer function solutions, which comprise a much smaller set of data, are imported to OPTCON and the STRESS module in SASSI2000 is implemented in OPTCON to compute element stresses. OPTCON combines the shell stresses into one 3-D record for design while preserving the maximum responses. OPTCON imports static loads, such as dead-load from SAP2000 [2] models. OPTCON module is a Windows program using a project database.

An earlier version of the OPTCON reinforced concrete design engine was developed 30 years ago and used extensively in the design of

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## ABBREVIATIONS, ACRONYMS, AND TERMS

ACI	American Concrete Institute
CG	center of gravity
DLL	Dynamic Link Library
DOF	degree(s) of freedom
FFT	fast Fourier transform
OPTCON	optimum concrete
SSI	soil-structure interaction

*The process streamlines the analysis and design process and reduces the engineering time for design significantly.*

nuclear power plants. [3] OPTCON optimizes its reinforcement design by considering all the factored shell forces at once, determining the “best-fit” reinforcement at each face of the concrete.

For the new integrated design approach, the OPTCON computer code was modified to affect the design as follows:

- Design is performed using the element shell forces as a function of time, obtained from the Dynamic Link Library (DLL) using factored time history loads, thus preserving the phasing of the response motions and combining with applicable static loads.
- OPTCON assures design is adequate for stresses for all time steps.
- OPTCON performs automatic element-grouping where forces on sections of elements need to be considered as a set.
- OPTCON uses parabolic stress-strain relationship for concrete.
- All design meets the requirements of ACI 349-01 (both shear walls as well as floor diaphragms are designed).
- Selective output includes the required reinforcement on each face of the wall or the slab, in each direction, for each element.
- Contour plots of shell forces and computed reinforcement are available to the designer.

The process streamlines the analysis and design process and reduces the engineering time for design significantly. The integrated process incorporates theoretical accuracy and engineering judgment and is a valuable tool in the design of next generation of nuclear power plants.

## METHODOLOGY

The integrated design methodology involves (1) seismic analysis of the overall structure using SASSI2000, (2) static analysis under the

non-seismic loads using the same model, and (3) design of the structural members using the OPTCON module. Each of these steps is described below.

### Seismic Analysis with SASSI2000

The computer program is widely used in the nuclear industry for seismic SSI analysis of structures and development of seismic responses for structural design and equipment design. In SASSI, the equation of motion is formulated in frequency domain and fast Fourier transform (FFT) techniques are used to convert the frequency domain solution to time domain solution. For each selected frequency of analysis, SASSI solves for the following equation of motion where  $[C]$  is a complex frequency-dependent dynamic stiffness matrix

$$\begin{bmatrix} C_{ii}^{III} - C_{ii}^{II} + X_{ii} & -C_{iw}^{II} & CC_{is}^{III} \\ -C_{wi}^{II} & -C_{ww}^{II} & 0 \\ C_{si}^{III} & 0 & C_{ss}^{III} \end{bmatrix} \begin{Bmatrix} U_i \\ U_w \\ U_s \end{Bmatrix} = \begin{Bmatrix} X_{ii} U_i' \\ 0 \\ 0 \end{Bmatrix} \quad (1)$$

and  $[K]$  and  $[M]$  are the global complex stiffness and mass matrices, respectively. Using the following subscripts, which refer to degrees of freedom (DOF) associated with different nodes (see **Figure 1**):

$$[C] = [K] - w^2 [M] \quad (2)$$

### Subscript Nodes

- $b$  the boundary of the total system
- $i$  at the boundary between the soil and the structure
- $w$  within the excavated soil volume
- $g$  at the remaining part of the free-field site
- $s$  at the remaining part of the structure
- $f$  combination of  $i$  and  $w$  nodes

Formulation of the dynamic stiffness and mass matrices is very similar to all other finite element codes. To include the SSI effects, SASSI2000 requires computation of the free-field motion  $U_i'$  in Equation 1 and the impedance matrix for all foundation interaction nodes  $X_{ii}$ . The impedance matrix is, in effect, a complex frequency-dependent spring and dashpot, which is interconnected to all other interaction nodes and is obtained from the point load solution for each interaction node.

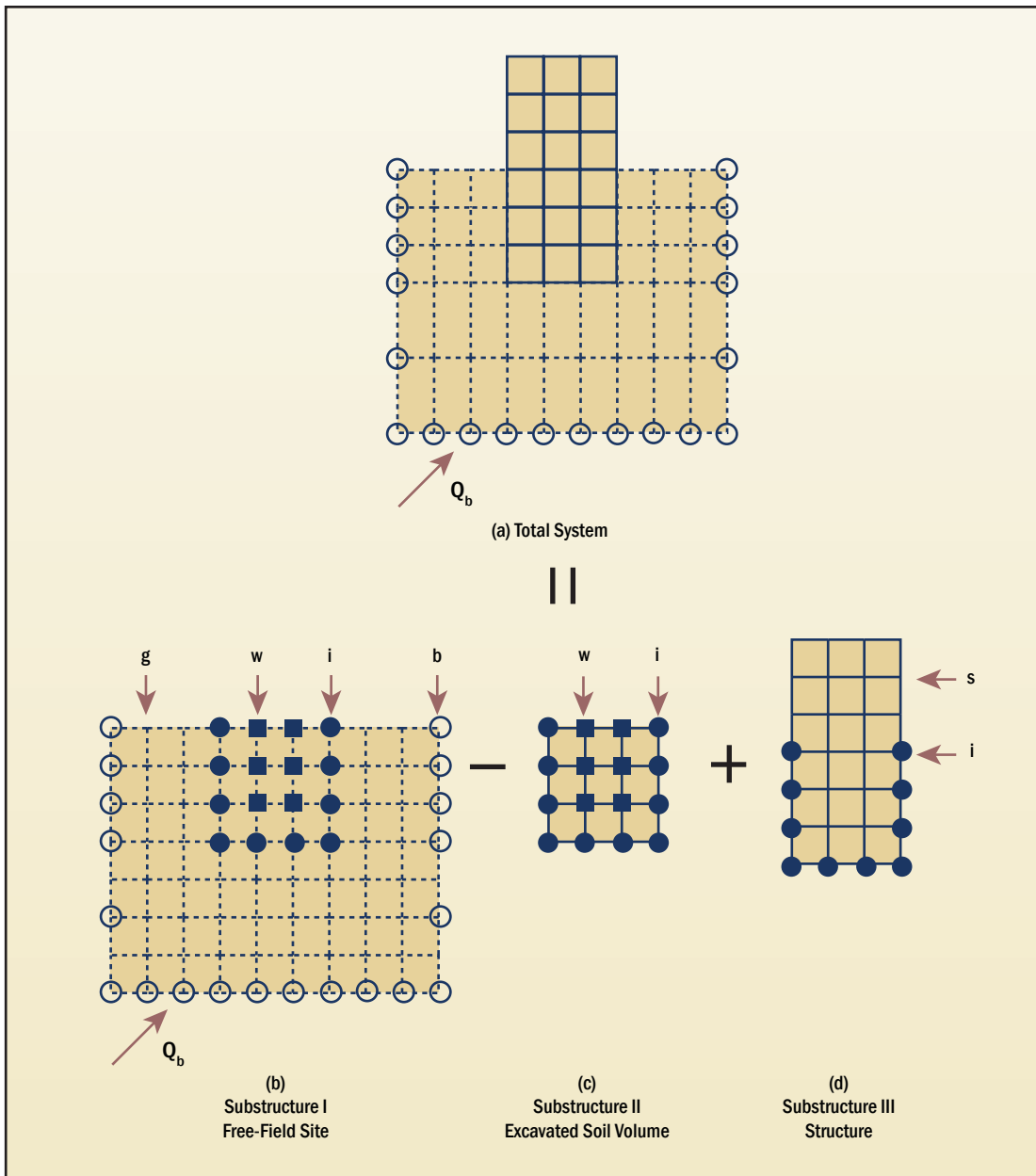


Figure 1. Substructuring Method in SASSI2000 Analysis

Figure 1 depicts the substructuring method used in SASSI2000 analyses. Details of SASSI2000 substructuring methods and the internal modeling can be obtained from the theoretical manual of the program (see [1]). The solution from Equation 1 in terms of  $U$  is the transfer function solution for each degree of the freedom in the model. The transfer function solution is convolved with the Fourier components of the input motion and converted to time domain to obtain the response time history for the respective degree of freedom in the model. The stress time histories for each element are computed from the response time histories of the nodes forming that element using the stress-strain relationship of the respective element.

#### Static Analysis for Non-Seismic Loads

The finite element model of the structure used in SASSI2000 for seismic analysis should be used for the non-seismic loads in accordance with the project criteria. Any general purpose finite element analysis program can be used for this purpose. In this study, SAP2000 is used. Since the design will be carried out for the total structure, it is necessary to capture the internal forces and moments for all members. Consequently, the finite element model must include the soil stiffness to capture the basemat response. Also, if the structure is embedded, the lateral soil pressures must be included in the static analysis.

The analysis results are saved in the project database that will be used during the design process.

### Definition of Design Forces

Design of shear wall structures has been carried out in the past using both element stresses and “cut section” forces. In the integrated approach, a combination of both is used as described below.

In the OPTCON program module, rows of elements in both walls and diaphragms are designated as “element-groups.” For each element-group, in-plane membrane forces and moments are calculated. For a wall, these forces are: membrane force in the vertical direction  $P_u$ , in-plane overturning moment  $M_u$ , and horizontal shear force  $V_u$ . For a diaphragm, these forces and moments would be calculated in both directions.

The out-of-plane design forces are calculated on an element basis, including the out-of-plane bending moments  $M_x$  and  $M_y$  and out-of-plane shears  $V_{xz}$  and  $V_{yz}$ .

All analysis is done on a time-step basis for the entire time-history duration using the 3-D combined shell stresses. At each time-step, the ACI 349-01 code criteria is considered so the envelope of the controlling design step is assured.

### Integrated Design Using the OPTCON Module

The shell stresses computed in the SASSI2000 STRESS DLL in OPTCON use the transfer-functions of the DOF defined by the connectivity of the 3-D shell finite element model. To do this, the SHL17 thin/thick shell element’s stress recovery routines were rewritten using complex arithmetic so that their inputs were the frequency domain nodal transfer-functions rather than the original nodal displacement time histories. The stress recovery was therefore performed in the frequency domain and converted to time domain using the SASSI2000 FFT routines. The time histories of shell element stresses are used for design. The SHL17 quadrilateral shell element has five output points where the shell stresses are computed; one is at the center of gravity (CG) of the element and the other four are located about 80 percent of the way from the CG to the corner nodes.

SASSI2000 performs the analysis one direction at a time (three runs for X-, Y-, and Z-excitation) and uses the three components of time histories,

one for each respective direction. Therefore, the process used by OPTCON is for the user to isolate all the shell elements to be considered in a design (i.e., a shear wall or a floor diaphragm) and then the internal STRESS DLL is executed three times, once for each of the global directions and the results of these analyses are saved to disk. Then, each of the three directional analyses is post-processed so the result is a combined 3-D time history record for each shell element in the analysis. During the 3-D combination, the three directions of excitations are permuted in terms of plus/minus sign for all eight possible combinations so that their maximum resulting shell stress components are captured. Thus, the final 3-D combined shell stresses contain all the time-history stress components— $S_{xx}$ ,  $S_{yy}$ ,  $S_{xy}$ ,  $M_{xx}$ ,  $M_{yy}$ ,  $M_{xy}$ ,  $V_{xz}$ , and  $V_{yz}$ —for each shell at all five stress output points on the SHL17 element.

Then, OPTCON uses the imported static shell stresses for dead-load and live-load along with user specified loading-combination scale factors and for each time-step combines them into the final shell element stresses to be used for design.

For element-based design (i.e., with no element-grouping) the final shell element stresses are used directly. In this, typically  $S_{xx}$  and  $M_{xx}$  are considered as  $P$  and  $M$  pairs at each time-step to design the horizontal reinforcement in the shear wall and  $S_{yy}$  and  $M_{yy}$  to design the vertical reinforcement. The twisting moment,  $M_{xy}$  is added to amplify both  $M_{xx}$  and  $M_{yy}$  so that the design at each time-step is conservative. OPTCON performs element-based design using the single shell element stresses using an iteration process where both  $A_s$  and  $A_s'$  are initially set to their minimums and then swept through all the steps so that all  $P$  and  $M$  pairs best-fit within a numerical reinforced concrete interaction diagram.

For element-groups, OPTCON automatically assembles the individual shell elements to be considered in the design into internal logical groups. This is accomplished considering openings in the designs such as doors and windows in shear walls or openings in floor diaphragms. Such openings form piers at each of the element-levels that, in certain cases, require special ACI 349-01 code considerations. Thus, OPTCON, with element-group design, always considers all possible cut-sections of groups of elements in the design at each element-level. **Figure 2** shows the element-grouping on a simple shear wall with one door opening.

All analysis is done on a time-step basis for the entire time-history duration using the 3-D combined shell stresses.

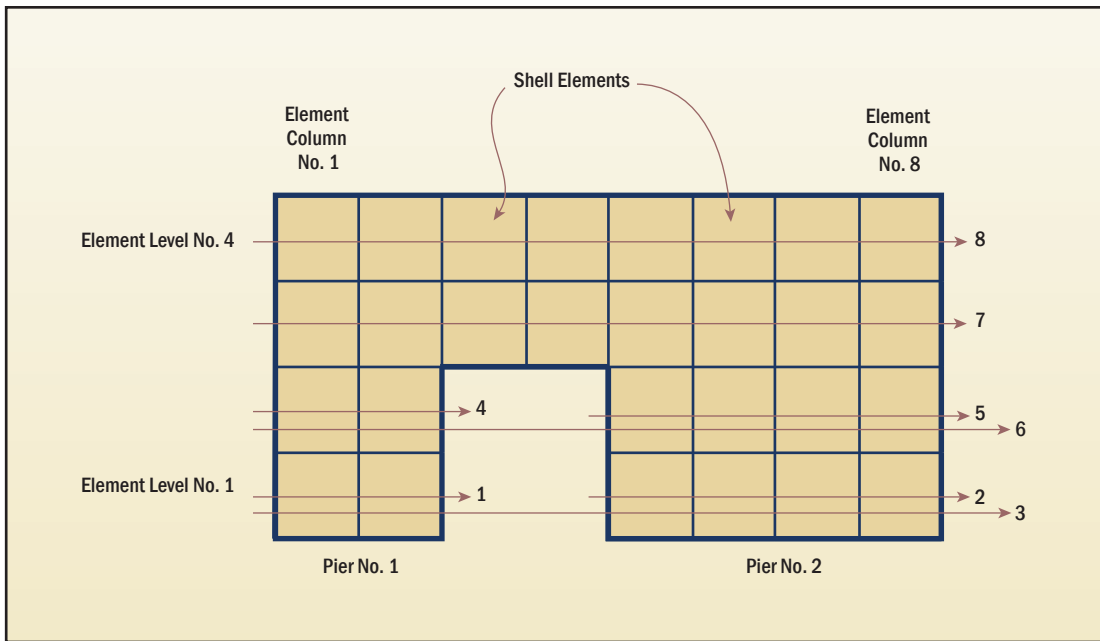


Figure 2. Elevation of Shear Wall with One Opening, Showing Horizontal Groups

When using element-grouping, the shell stresses at the five output points on the element are averaged.

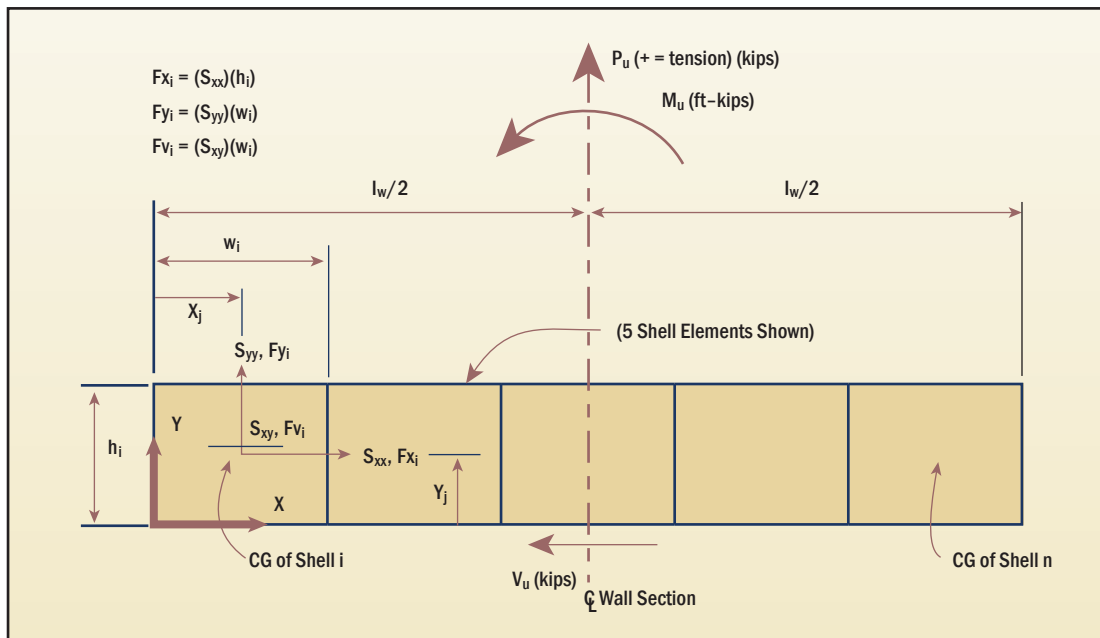


Figure 3. Integration of CG Shell Stresses to Determine Design Forces and/or Moments – Five-Element Group

In Figure 2, vectors 1, 2, 4, and 5 represent cut-sections on the wall piers to be used for design. Vectors 3 and 6 are cut-sections on multiple piers, and vectors 7 and 8 are cut-sections on the wall where no piers exist, across the whole wall.

When using element-grouping, the shell stresses at the five output points on the element are averaged and assumed to be located at the CG of the element. Then, the individual CG

shell stresses are integrated at each time step to determine the design forces and/or moments. Figure 3 shows how these integrations are performed using an example of a five-element group:

*Applied Axial Load on Wall (tension is positive):*

$$P_u = \sum_{i=1}^{i=n} Fy_i \quad (3)$$

*Applied Moment about Center Line of Wall or Wall Segment (counter-clockwise is positive):*

$$M_u = \sum_{i=1}^{i=n} \left\{ Fy_i \times \left( \frac{l_w}{2} - x_i \right) \right\} \quad (4)$$

*Applied Shear Load on Wall:*

$$V_u = \sum_{i=1}^{i=n} Fv_i \quad (5)$$

#### Concrete Stress Block

When designing reinforcing steel with element-groups while considering membrane forces and their overturning moments, OPTCON considers equally distributed rebar located along the section to be designed. **Figure 4** shows the design of a typical cut-section where no openings exist:

*Strain in Rebar Set,  $e_s$ , as a Function of the Strain of the Concrete,  $e_c$ , at the Edge of the Concrete Sections:*

$$e_s = e_c \left( \frac{x_i - L_{na}}{L_{na}} \right) \quad (6)$$

*(strain, i.e., inches per inch)*

*Stress in Bar Set:*

$$f_s = e_s E_s \leq 0.9 f_y \quad (7)$$

*(force per unit of area)*

*Force in Bar Set:*

$$F_s = f_s \times A_s \text{ (units of force)} \quad (8)$$

NOTE: Forces on bar sets in compression zone are reduced to consider force taken by concrete.

If openings such as doors or windows should exist in the cut-section shown in Figure 4, OPTCON iterates on the area of reinforcement considering differing concrete stress block having discontinuities and the reinforcing steel is not considered where the openings exist.

#### DESIGN EXAMPLE

The integrated approach was applied to a shear wall structure in a high seismic zone. The two-story building is approximately 150 ft x 250 ft and 64 ft high. As can be observed from this model, numerous openings exist in the walls and slabs and therefore the design forces must be calculated considering these discontinuities.

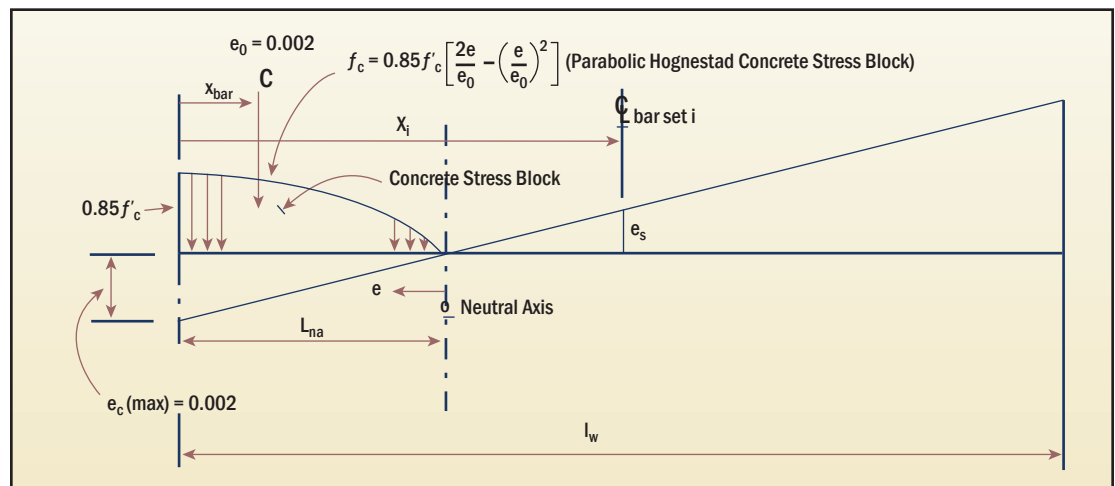
The finite element model for this building is shown in **Figure 5**. The model used a 5 ft x 5 ft mesh size, resulting in 9,000 nodes and 8,000 elements.

The design of the lower exterior shear wall illustrated in Figure 5 is shown as an example below. The shear wall runs from the basemat at elev. 0.0 to the first floor at elev. 27.27 and is 206 ft long, extending across the entire building. **Figure 6** illustrates the shell element mesh in the wall segment used in the example.

The shear wall has three shear panels—numbered 4, 5, and 6—formed by intersecting interior walls as shown above.

**Figure 7** is a contour plot of the  $S_{yy}$  shell forces in units of kips per foot of shell width. These are the absolute value of the maximum 3-D combined seismic plus static vertical shell forces in the wall. This is an illustration of a plot of the eight shell stress components that may be viewed at the option of the engineer. These plots are for information only and are used

When designing reinforcing steel with element-groups while considering membrane forces and their overturning moments, OPTCON considers equally distributed rebar located along the section to be designed.



**Figure 4. Design of a Typical Cut-Section with No Openings**

to view the stress concentrations that tend to dominate the design of the reinforcing steel.

**In-Plane Reinforcement Requirements**

The entire wall was checked using OPTCON with element-grouping for limiting shear

strength per Section 21.6.5.6 of ACI 349-01. The largest demand-capacity ratio for individual piers was 0.45 and the largest for piers sharing a common lateral force was 0.39.

Horizontal shear reinforcement was designed with OPTCON, using element-grouping to meet

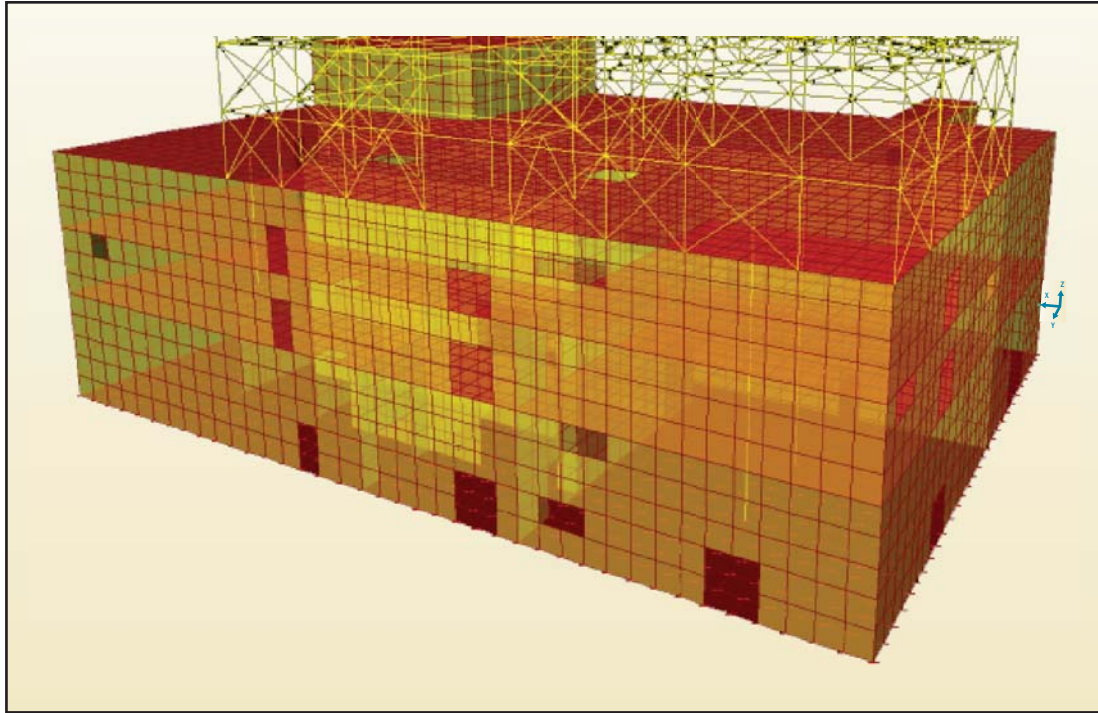


Figure 5. Example of Shear Wall Structure

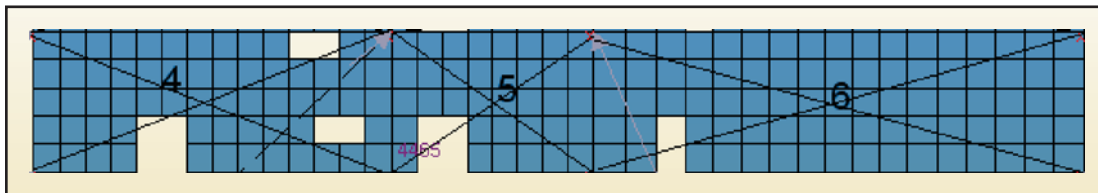


Figure 6. Lower Exterior Shear Wall

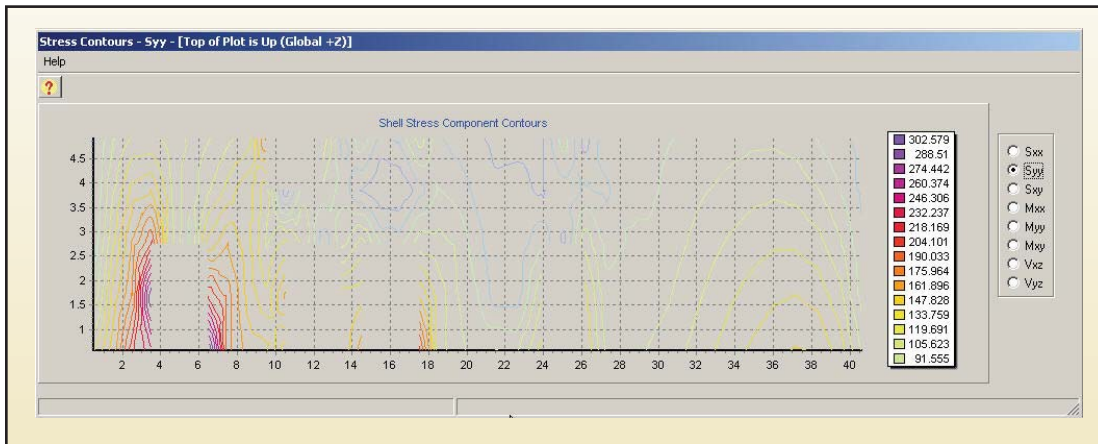


Figure 7. Contour Plot of S<sub>yy</sub> Shell Membrane Forces

The integrated design approach presented in this paper takes advantage of the time history phase relationship of the seismic forces and also optimizes the design.

the provisions of ACI 349-01, equations 21-7, 11-31, and 11-32 of ACI 349-01. The controlling reinforcement designed was 0.86 sq.-in. per foot of shell width per face.

Shear-friction was checked at the bottom of the wall (basemat intersection) using element-grouping per paragraph 11.7 of ACI 349-01 but did not control.

#### Reinforcement Required Resulting From Out-of-Plane Loads on the Wall

OPTCON was used with element-based design using only the shell moments  $M_{xx}$  and  $M_{yy}$ , amplified by  $M_{xy}$  with the membrane forces  $S_{xx}$  and  $S_{yy}$  set to zero (since they had already been considered in the in-plane design above). This resulted in the added reinforcement needed to resist the out-of-plane loadings on the wall.

#### RESULTS

The total reinforcement was obtained by combining reinforcement required for in-plane loadings with the added reinforcement required to resist out-of-plane loadings and considering minimum code requirements. The proposed approach resulted in reinforcement requirements that were 77%–93% of the reinforcement determined using the two-step approach.

No out-of-plane reinforcements (stirrups) were required in the wall during the design.

#### CONCLUSIONS

Adequate tools are important for the design of complex structures for both commercial nuclear power plants and US Department of Energy facilities. The integrated design approach presented in this paper takes advantage of the time history phase relationship of the seismic forces and also optimizes the design to provide a balanced design. This design tool will accelerate the design process and, at the same time, will minimize the peer review process that has become a large part of such projects.

The example design shown above was accomplished in less than 3.5 hours using a high-end PC running the OPTCON Windows program.

Because the design process meets the ACI code requirements, it can be readily applied to complex projects. ■

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#### BIOGRAPHIES



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Thomas served on the Senior Structural Staff in the Bechtel Los Angeles Office and managed the Containment Specialty Group that performed front-end design for Nuclear Containment design in the 1970s. His specialty is modern windows software engineering as applied to Finite Element Analysis and optimized reinforced concrete design meeting the requirements of ACI 349 and ACI 359 Codes, directly related to time-history design due to combined static and seismic loading.

Thomas holds a BS in Civil and Structural Engineering from the University of Southern California, Los Angeles.



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As a senior principal engineer, he provides support to various projects and performs design reviews and independent peer reviews. The scope of work includes development of design criteria, seismic evaluations, structural evaluations and investigations, technical review and approval of design, serving as Independent Peer Reviewer for special projects, investigation and resolution of design and construction issues, and supervision of special analyses.

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