

Effective In-plane Stiffness for Finite Element Analysis of SC Walls

Hyuk-jin Kwon ^a, Hong-gun Park ^{a*}

^aDepartment of Architecture and Architectural Engineering, Seoul National University, 1 Gwanak-ro, Seoul, 08826, Republic of Korea

*Corresponding author: parkhg@snu.ac.kr

***Keywords :** steel-plate composite wall, effective in-plane stiffness, finite element analysis, nuclear structures

1. Introduction

Steel-plate composite (SC) shear walls offer excellent constructability and seismic resistance, but concrete cracking causes spatially varying stiffness degradation that complicates seismic finite-element analysis. Existing standards, including **AISC N690 Appendix N9**, and **KEPIC-SNG**, provide simplified effective stiffness procedures, largely derived from pure shear behavior. However, actual wall elements experience combined flexural and shear actions, producing multiaxial stresses and variable crack orientations. This study develops a rational, practical effective in-plane stiffness model for SC walls through theoretical investigation, nonlinear FEA, experimental comparisons, and evaluation of current design provisions.

2. Assessment of current design provisions

Both **N690-N9** and **SNG** determine effective in-plane shear stiffness from secant relationships between cracking and yielding. A major difference is the assumed concrete shear cracking strength: **N690-N9** adopts $0.17\sqrt{f_c}$, whereas **SNG** adopts $0.31\sqrt{f_c}$ following **JEAG-4618**. Although some isolated pure-shear tests reported values near $0.17\sqrt{f_c}$, those tests introduced load directly into the concrete and transferred it to the faceplates through bond, causing boundary stress concentrations, localized cracking, premature plate buckling, and weld tearing. Experimental evidence from walls subjected to more representative combined bending and shear indicates that the cracking strength of SC walls is comparable to that of reinforced concrete (RC) walls and is better represented by $0.31\sqrt{f_c}$. Using an excessively low value is not necessarily conservative in seismic analysis because it can underestimate stiffness, seismic forces, and the share of load attracted by SC walls.

Theoretical constitutive analysis and nonlinear finite element analysis (NLFEA) were performed for SC panels with steel plate ratios of 2%, 3%, 4%, and 6% (see **Fig. 1**). The concrete was modeled as isotropic before cracking and orthotropic after cracking, incorporating tension stiffening and nonlinear compression behavior, while the steel faceplates remained elastic. **N690-N9** underestimated stiffness at low and intermediate load levels because it predicted early cracking, but its secant stiffness at approximately 80% of nominal shear strength agreed with **NLFEA**. **SNG** reproduced the cracking

point more reasonably but underestimated stiffness at higher load levels by assuming a fully cracked concrete section. A rational pure-shear representation can therefore combine the cracking strength and degradation curve of **SNG** with the fully cracked stiffness of **N690-N9**.

The comparison also showed a broader limitation of shear-based provisions. SC walls retain higher post-cracking stiffness than comparable RC walls because continuous faceplates provide direct shear resistance in addition to the concrete-strut mechanism. Nevertheless, applying **ASCE 4-16** to RC walls and **N690-N9** or **SNG** independently to SC walls can assign greater effective stiffness to cracked RC walls than to SC walls. This inconsistency can distort the relative stiffness and load distribution in hybrid RC-SC nuclear structures. Moreover, the existing SC provisions performed reasonably for squat, shear-dominated walls but significantly underestimated the secant stiffness of slender walls, where the uncracked compression zone continues to provide substantial flexural rigidity.

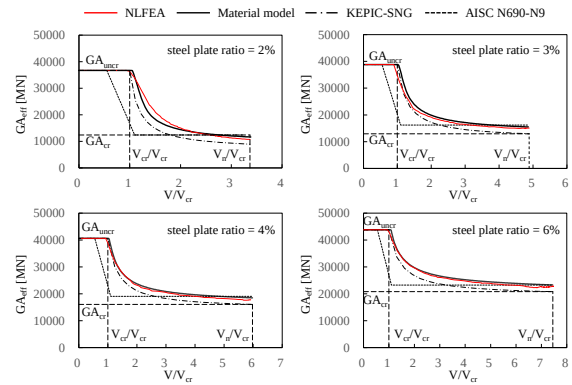


Fig. 1. Variation of effective shear stiffness according to steel plate ratios

3. Proposed effective stiffness models and validation

For routine linear analysis, the study proposed representing cracked concrete with an equivalent isotropic elastic modulus while retaining the full elastic modulus of the steel faceplates. The model was derived from cyclic-test data for 48 rectangular and 17 flanged SC walls. The effective stiffness ratio at yield averaged approximately 0.60, nearly independent of cross-sectional configuration and steel plate ratio. When the elastic contribution of the faceplates was separated, the

mean concrete stiffness reduction factor at the design-basis earthquake or safe-shutdown earthquake level was 0.45 for rectangular walls and 0.50 for flanged walls, with standard deviations of 0.09 and 0.14, respectively. At the operating-basis earthquake level, an effective concrete modulus of $0.8E_c$ was obtained for both wall types. Because nuclear wall systems generally contain intersecting flange walls, $0.5E_c$ is recommended for cracked SC concrete at the higher seismic demand level; the steel faceplates retain E_s .

These recommendations were implemented as **Proposed Model 1**, as summarized in **Table 1**. **Proposed Model 2** instead used a stress-state-dependent orthotropic stiffness matrix updated according to each element's principal stresses and crack direction. The two models were compared with experiments, current provisions, and **NLFEA** for five SC wall specimens, including three rectangular and two flanged walls.

The current provisions predicted squat-wall stiffness satisfactorily but underestimated the slender specimen with an aspect ratio of 3.3. **Model 1** achieved comparable accuracy for squat walls and improved the prediction for the slender wall, although some underestimation remained. **Model 2** produced secant stiffness values essentially identical to **NLFEA** for the rectangular specimens and agreed well with the experiments. Differences for flanged specimens were mainly attributed to discontinuous faceplates at test-wall intersections, whereas actual nuclear walls generally use continuous faceplates.

For analyses requiring local stress redistribution and crack-orientation effects, the stress-dependent updating of **Model 2** was automated through tension crack analysis (TCA). In this procedure, steel is linear elastic and concrete remains elastic in compression; only tensile-cracking-induced stiffness degradation is modeled. A four-layer shell section, consisting of steel faceplate, half of the concrete infill, half of the concrete infill, and steel faceplate, enables efficient treatment of in-plane forces, out-of-plane bending, and thermal gradients. Comparisons covering wall aspect ratios of 0.5, 1.0, and 2.0 and axial load ratios from 0.0 to 0.3 showed that **TCA** closely reproduced **NLFEA** until steel yielding for rectangular walls and up to approximately 80% of maximum strength for flanged walls. Because compressive nonlinearity and crushing are omitted, **TCA** should not be used beyond concrete crushing.

4. Conclusions

The study demonstrates that effective stiffness based solely on pure-shear behavior cannot consistently represent SC walls subjected to combined flexure and shear. For routine modal, response-spectrum, and linear time-history analysis, the proposed equivalent-modulus approach offers a simple and rational representation: use $0.8E_c$ for uncracked element, approximately $0.5E_c$ for the cracked element, and retain E_s for the faceplates. For detailed structural analysis, **TCA** automatically accounts for tensile cracking without manual element-by-element stiffness updates. It reproduced the relevant pre-yield response with accuracy comparable to conventional **NLFEA** while requiring only about 10% of the computational time and showing improved numerical robustness. Together, the two procedures provide a practical hierarchy of analysis methods and support more realistic stiffness distribution and load sharing in both SC and hybrid RC-SC nuclear structures.

REFERENCES

- [1] AISC N690, 2024. Specification for Safety-Related Steel Structures for Nuclear Facilities. American Institute of Steel Construction, Chicago, IL.
- [2] Epackachi, S., Nguyen, N.H., Kurt, E.G., Whittaker, A.S., Varma, A.H., 2015. In-plane seismic behavior of rectangular steel-plate composite wall piers. J. Struct. Eng. 141 (7).
- [3] JEAG-4618, 2005. Technical Guidelines for Aseismic Design of Steel Plate Reinforced Concrete Structures—Buildings and Structures. Japan Electric Association, Japan.
- [4] KEPIC-SNG, 2023. Nuclear Safety Related Steel Structures: Steel-Plate Concrete Structure. Korea Electric Association, Seoul, Korea.
- [5] Ozaki, M., Akita, S., Osuga, H., Nakayama, T., Adachi, N., 2004. Study on steel plate reinforced concrete panels subjected to cyclic in-plane shear. Nucl. Eng. Des. 228, 225–244.

Table 1: Application of proposed models for seismic and structural analysis

Type	Concrete	Steel plate
Uncracked	$0.8E_c$	E_s
Proposed model 1	$0.5E_c$	
Proposed model 2	Updated from local principal stress and crack direction	