U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

Structural Assessment of Thick Concrete Shear Walls Compared to Test Data

CSNI Workshop on *Ageing Management of Thick Walled Concrete Structures, including ISI, maintenance and repair – Instrumentation methods and Safety Assessment in view of long term operation*

Prague – Czech Republic

October 1-3, 2008

Syed Ali, Senior Technical Advisor for Civil/Structural Issues
Office of Nuclear Regulatory Research

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Topics

- Introduction
- Relevant JNES/NUPEC reinforced concrete shear wall tests
- Evaluation of simplified methods
  - Methods for ultimate shear capacity estimation
  - Method for inelastic absorption factor estimation
- ANACAP finite element analyses
  - Static analyses of cyclic loadings
  - Transient analysis for shaking table tests
  - Damage accumulation effect
- Conclusions

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Introduction

- JNES/NUPEC 10 year testing program for investigation of the behavior of reinforced concrete shear walls under cyclic loadings and strong seismic loadings
  - Element tests and box- and cylinder- type shear walls
  - Static cyclic loadings and shaking table tests
  - Shear walls were loaded to incipient failures
- JNES/NUPEC shear wall tests provide a unique opportunity for validation of practical methods
  - These methods were previously validated using single element shear walls
- Analysis of these test results was part of collaborative efforts between US and Japan on seismic issues
  - The collaboration included a series of technical meetings to review and evaluate test and analytical results

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Introduction (cont.)

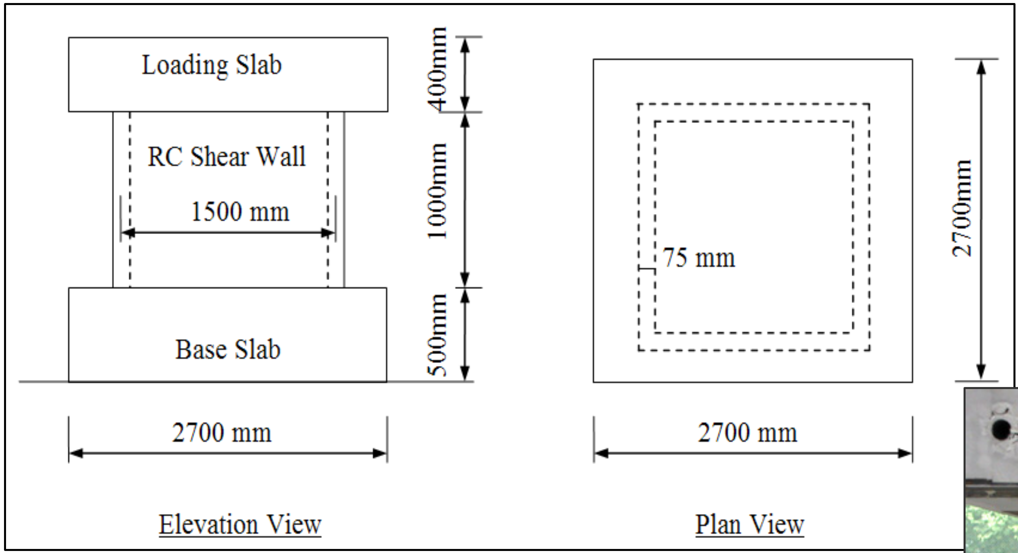
- Objectives
  - Assess analysis methods for seismic shear wall capacity
  - Determine the technical significance of the JNES/NUPEC test data related to the effects of out of plane motions on the overall methodology
- Evaluated simplified methods including two ACI 349-01 methods and one ASCE 43-05 method for ultimate shear capacity estimation
- This paper summarizes results from NRC/BNL’s evaluations of methods using these test results
- More detailed information in NUREG/CR-6925

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

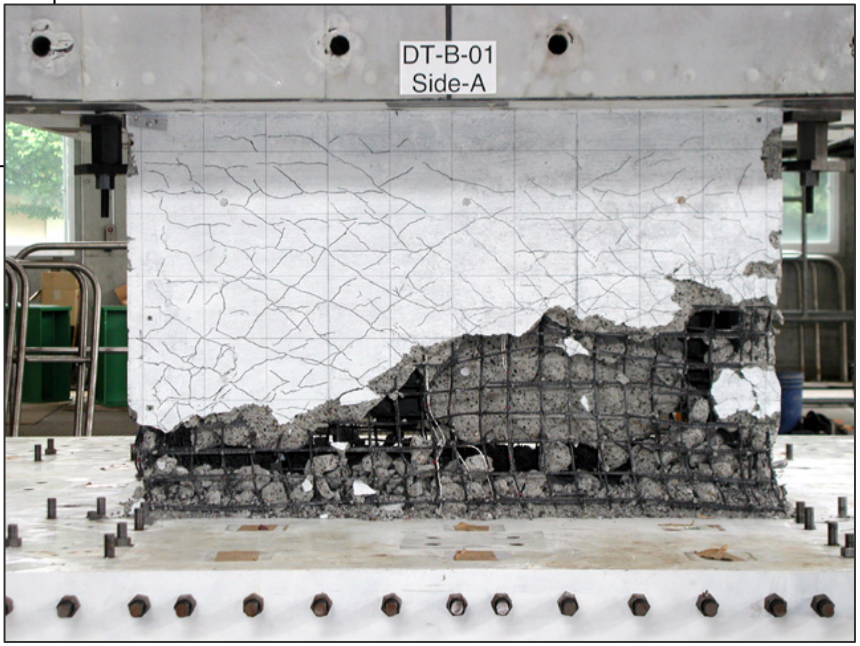
Relevant JNES/NUPEC Shear Wall Tests

- Only box type shear wall specimens were considered in the analyses
- 1.5 m x 1.5 m center to center in plan
- 75 mm thick
- Heights were 0.7 m, 1.0 m, or 1.3 m
- Base slab and loading slab for static cyclic test specimens
- Base slab, top slab, and added weight for shaking table test specimens
- Reinforcement ratio of 1.2%

JNES/NUPEC Shear Wall Specimens



11 Static Cyclic Test Specimens were used for NRC/BNL analyses



DT-B-01 and DT-B-02 were tested; DT-B-02 was used for NRC/BNL analyses

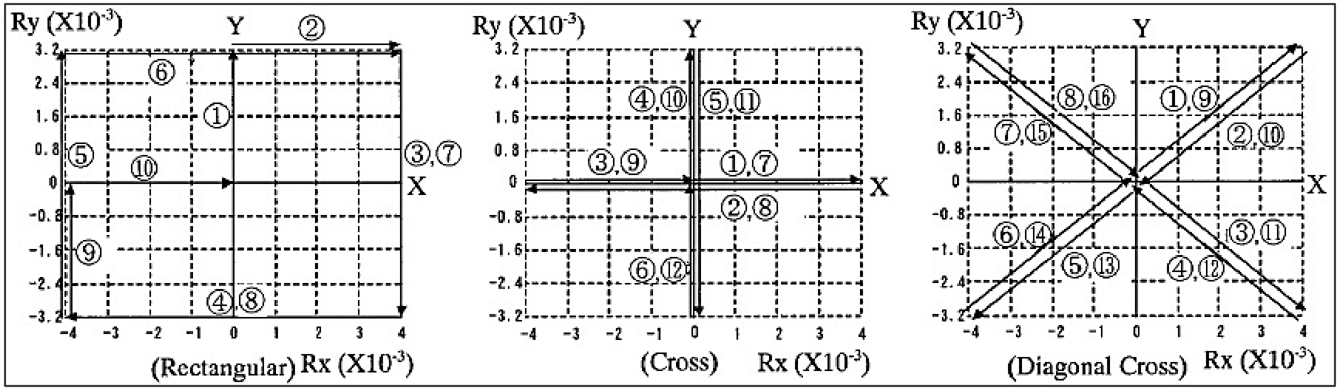
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

JNES/NUPEC Shear Wall Specimens – Static Cyclic Tests

Table 1 Specimen Properties and Shear Strengths

Specimen	f'_c (MPa)	f_y (MPa)	h_w (m)	h_w / l_w	V_{MT} (kN)	V_{VT} (kN)
SD-06-00	30.7	345	0.7	0.47	1686	1686
SD-06-26	29.2	345	0.7	0.47	*1604.11	1794
SD-06-45	33.2	345	0.7	0.47	*1297.54	1835
SD-08-00	34.9	345	1	0.67	1480	1480
SD-08-26	34.8	345	1	0.67	*1401.14	1567
SD-08-45	37.4	345	1	0.67	*1161.07	1642
SB-B-01	41.3	375	1	0.67	1381	1600
SB-B-02	39.7	375	1	0.67	1596	1596
SB-B-03	34.9	375	1	0.67	1261	1588
SD-10-00	37.8	345	1.3	0.87	1231	1231
SD-10-45	37.2	345	1.3	0.87	*943.28	1334

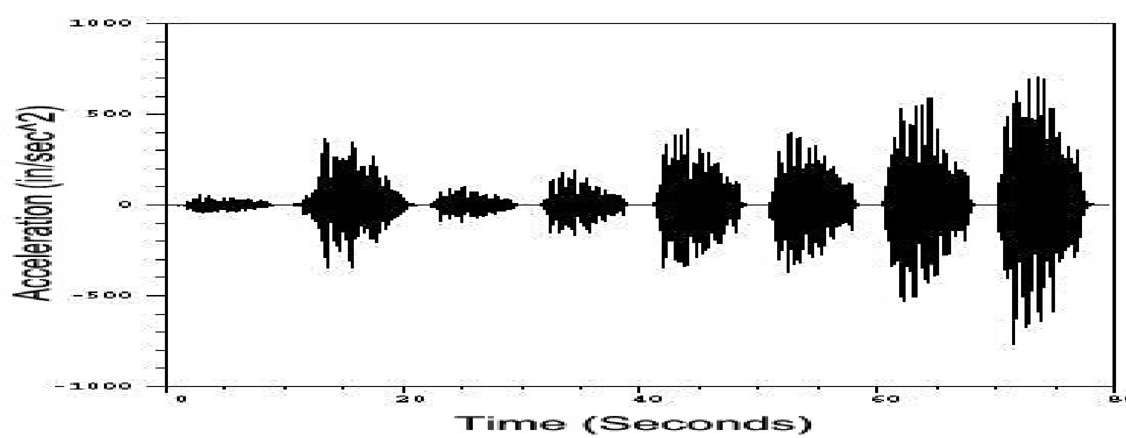
* calculated value by BNL.



JNES/NUPEC Shear Wall Specimens – Shaking Table Tests

- Added weight resulting in an axial pressure of 1.47 MPa at the bottom of the shear walls
- A total weight of 67 ton
  - Ix = Iy = 71.7 ton-m^2 and Iz = 112 ton-m^2
- A total of nine runs
  - 1, 2, 2', 3, 3', 4, 5, 6, and 7
  - DT-B-02 failed in run 7
  - Analyses were performed for the first 8 runs
- Each run consists of two horizontal input motions and vertical motions (rocking and rolling)

X Input Motions



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

A Few Definitions

- Aspect Ratio = h_w / l_w
- Calculated ultimate shear strength = V_U
- Test shear strength = V_{MT}
- Test vector shear strength = V_{VT} (considering walls in both directions)
- Interaction intensity = V_{VT} / V_{MT}
  - $V_{VT} / V_{MT} = 1.0$ → no interaction (one directional loading)
  - $V_{VT} / V_{MT} = 1.414$ → maximum interaction (two directional loadings with equal magnitude)
  - When seismic shear forces from two horizontal directions are combined by 100-40-40 rule (neglecting vertical motions), $V_{VT} / V_{MT} = 1.077$

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Simplified Methods for Ultimate Shear Strength Estimation

- ACI 349-01 Chapter 11 Method
- ACI 349-01 Chapter 21 Method
- ASCE/SEI 43-05 method
- All specified for single element shear walls
  - No direct consideration of complex shear wall systems and out of plane loadings
- No strength reduction factor, ϕ, in order to obtain an estimate of the ultimate capacity

ACI 349-01 Chapter 11 Method

- Section 11.10, “Shear and Torsion”
- Shear strength contribution from concrete, vertical load, and horizontal reinforcement
- Upper bound ACI code limit governs all cases
- Ratios V_U / V_{VT} and $V_U / V_{MT} < 1$
  - indicates that the ACI 349 Chapter 11 method is conservative for all cases.
- The level of conservatism is very large for smaller aspect ratios
- The level of conservatism diminishes as the aspect ratio increases to 0.87

Table 2 Summary of Results using ACI 349 Chapter 11 Method

Specimen	h_w / l_w	V_U (kN)	V_U / V_{VT}	V_U / V_{MT}
SD-06-00	0.47	828.14	0.491	0.491
SD-06-26	0.47	807.65	0.450	0.504
SD-06-45	0.47	861.19	0.469	0.664
SD-08-00	0.67	882.97	0.597	0.597
SD-08-26	0.67	881.70	0.563	0.629
SD-08-45	0.67	914.05	0.557	0.787
SB-B-01	0.67	960.52	0.600	0.696
SB-B-02	0.67	941.73	0.590	0.590
SB-B-03	0.67	882.97	0.556	0.700
SD-10-00	0.87	918.92	0.747	0.747
SD-10-45	0.87	911.60	0.683	0.966

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

ACI 349-01 Chapter 21 Method

- Section 21.6, "Special Provisions for Seismic Design"
- Shear strength contribution from concrete and horizontal reinforcement
- Upper bound ACI code limit governs all cases, as for Chapter 11 method
- Most ratios V_U / V_{VT} and V_U / V_{MT} < 1
  - Except for case SD-10-45
- The level of conservatism is large for smaller aspect ratios and diminishes as the aspect ratio increases
- For case SD-10-45
  - Conservative if interaction is considered (V_U / V_{VT} =0.854)
  - Interaction intensity V_{VT} / V_{MT} = 1.414 is not realistic for practical purposes

Table 3 Summary of Results using ACI 349 Chapter 21 Method

Specimen	h_w / l_w	V_U (kN)	V_U / V_{VT}	V_U / V_{MT}
SD-06-00	0.47	1035.17	0.614	0.614
SD-06-26	0.47	1009.56	0.563	0.629
SD-06-45	0.47	1076.49	0.587	0.830
SD-08-00	0.67	1103.71	0.746	0.746
SD-08-26	0.67	1102.13	0.703	0.787
SD-08-45	0.67	1142.56	0.696	0.984
SB-B-01	0.67	1200.65	0.750	0.869
SB-B-02	0.67	1177.16	0.738	0.738
SB-B-03	0.67	1103.71	0.695	0.875
SD-10-00	0.87	1148.65	0.933	0.933
SD-10-45	0.87	1139.50	0.854	1.208

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

ASCE/SEI 43-05 method

- ASCE/SEI 43-05, “"Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities“
- Section 4.2.3, "Capacity of Low Rise Concrete Shear Walls
- Based on the empirical method initially developed by Barda [Barda, Hanson, and Corley, 1976]
- Shear strength contributions from concrete, vertical load, and steel reinforcements in both horizontal and vertical directions
- Applicable to shear walls with aspect ratios <= 2

ASCE/SEI 43-05 method

- Two factors affecting the accuracy
  - Aspect ratio
    - V_U / V_{MT} : between 0.82 and 1.09 for $h_w / l_w = 0.47$; V_U / V_{MT} : between 0.92 and 1.20 for $h_w / l_w = 0.67$; V_U / V_{MT} : between 1.09 and 1.41 for $h_w / l_w = 0.87$
    - when there is no interaction, i.e., $V_{VT} / V_{MT} = 1$, V_U / V_{MT} increases from 0.82 to 1.09 as the aspect ratio increases
  - Interaction intensity
    - tends to over predict the shear strength as the interaction intensity grows
- Compared to ACI 349-01 methods
  - Less conservative for most cases
  - More accurate
  - Can be non-conservative for cases with a large aspect ratio and/or interaction intensity

Table 4 Summary of Results using ASCE/SEI 43-05 Method

Specimen	h_w / l_w	V_U (kN)	V_U / V_{VT}	V_U / V_{MT}	V_{VT} / V_{MT}
SD-06-00	0.47	1383.89	0.821	0.821	1
SD-06-26	0.47	1366.65	0.762	0.852	1.118
SD-06-45	0.47	1411.70	0.769	1.088	1.414
SD-08-00	0.67	1369.98	0.926	0.926	1
SD-08-26	0.67	1369.00	0.874	0.977	1.118
SD-08-45	0.67	1394.01	0.849	1.201	1.414
SB-B-01	0.67	1483.95	0.928	1.075	1.159
SB-B-02	0.67	1469.42	0.921	0.921	1
SB-B-03	0.67	1423.98	0.897	1.129	1.259
SD-10-00	0.87	1335.30	1.085	1.085	1
SD-10-45	0.87	1330.13	0.997	1.410	1.414

ASCE/SEI 43-05 method

- Optimum Regression Equation (ORE)

- ORE

$$\frac{V_U}{V_{MT}} = F\left(\frac{V_{VT}}{V_{MT}}\right)^{0.8}$$

$$F = 0.5 + 0.65\frac{h_w}{l_w}$$

- *F* is a linear function of aspect ratio
- *F* can be an adjustment factor for ASCE/SEI 43-05 method to be more accurate
- Rearranged ORE in the shape of a unit circle

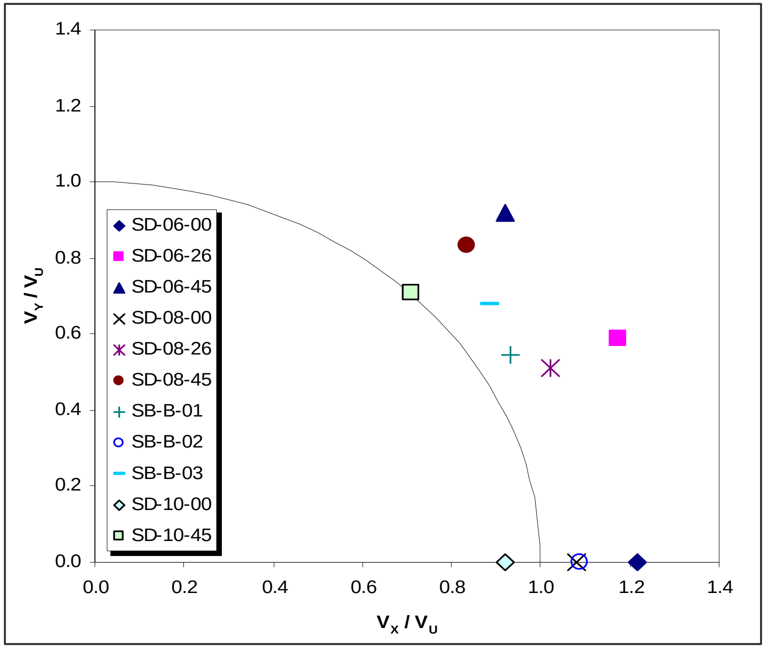
$$\left(\frac{V_{VT}}{V_U / F}\right) = \left(\frac{V_{VT}}{V_{MT}}\right)^{0.20}$$

- Right hand side represents the bias from interaction intensity after application of factor *F*
  - Maximum is 7.2%

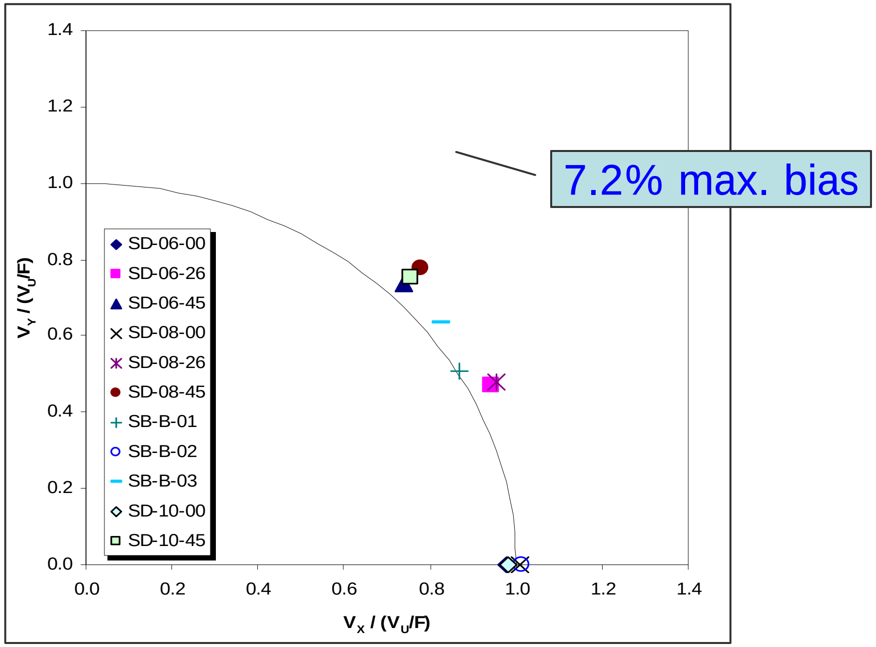
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Factor *F* for ASCE/SEI 43-05 method

$$\left(\frac{V_X}{V_U}\right)^2+\left(\frac{V_Y}{V_U}\right)^2=1 \qquad \left(\frac{V_X}{V_U/F}\right)^2+\left(\frac{V_Y}{V_U/F}\right)^2=1$$



Before Application of *F*



After Application of *F*

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Inelastic Energy Absorption Factor

- Inelastic energy absorption factor as a measure of a structure's capacity to absorb earthquake energy inelastically
  - To reduce the linearly calculated response spectra (demand)
  - Or, to increase the capacity of a structure
- Four methods evaluated
  - Ridell-Newmark method, point estimate method, secant frequency method, spectral averaging method
- Run 6 of the shaking table test DT-B-02 was used
  - Elastic structural frequency prior to Run 1: 20.6 Hz and 20.4 Hz in the X and Y directions, respectively
  - Natural frequencies dropped to 13.0 Hz and 11.5 Hz prior to Run 6
  - Damping is estimated to be 5%

United States Nuclear Regulatory Commission
Protecting People and the Environment

Inelastic Energy Absorption Factor

– Comparisons to the estimate from test

- Estimated F_μ from the test is 3.85
- The secant frequency method provided the most accurate overall comparison to the test result
  - For this particular specimen configuration and earthquake motion, the effect of the multi-directional excitation did not significantly affect the calculation of the inelastic energy absorption factor

Table 5 Comparison of Predicted Versus Estimated F_μ Factors

(Run 6, Y-direction, estimated Fμ =3.85)

Method	Predicted F_μ		% Deviation From Estimated	
	X	Y	X	Y
Riddell-Newmark Method	3.11	3.14	-19.2%	-18.2%
Eff. Freq/Eff Damping Methods				
Point Estimate	4.70	4.94	+22.1%	+28.3%
Spectral Averaging	4.36	5.10	+12.5%	+33.2%
Secant Freq. Limit	3.32	4.08	-13.8%	+6.0%

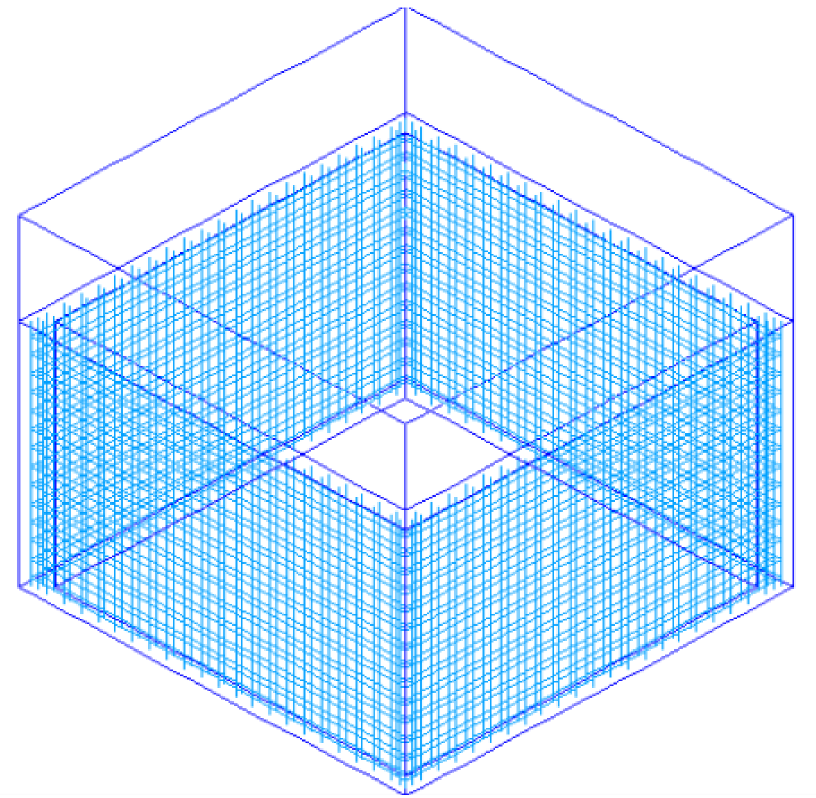
ANACAP Analyses

- ANACAP Version 3
- Especially suitable for static and dynamic nonlinear analysis of reinforced concrete structures
  - Capability to predict the structural performance before and after significant cracks developed
  - A unique approach fostered by ANATECH
- Modeling techniques
  - Smeared cracks at integration points
  - Strain hardening and softening of unconfined concrete under uniaxial compression
  - Redistribution of loads, particularly to rebars, by the cracking mechanism
  - Shear retention model and shear shedding model for crack surfaces
  - Rebars modeled as sub-elements
    - Can simulate the rebar plasticity, bond slip, and anchorage losses
  - A modified Raleigh damping implementation compatible with the damage state of the concrete

United States Nuclear Regulatory Commission
Protecting People and the Environment

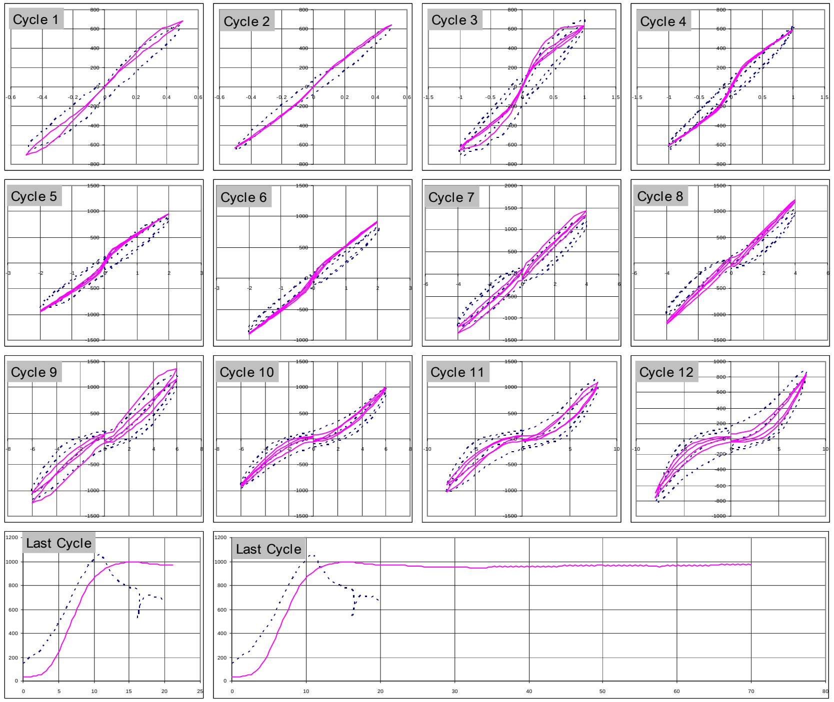
Static Cyclic Analyses

- Four loading patterns analyzed
  - 1-D (SD-08-00), rectangular (SB-B-01), cross (SB-B-02), and diagonal cross (SB-B-03)
- Finite element model
  - Fixed boundary condition at the base of the shear walls (to simulate rigid base slab)
  - Rigid loading slab
  - Displacement loading patterns applied at the center of the bottom face of the loading slab
  - Detailed rebar modeling



Static Cyclic Analyses - Assessment

- Predicted well the stiffness and the strength
  - Especially the post-ultimate performance
  - Remarkably for the hysteresis loops of large curvature for the last 3 cycles
- All predicted base shear capacities are higher than those of the tests
- The relative errors are mostly around 10%, with one exception that results in a relative error of 21%.
  - These errors are well within the general acceptable range for reinforced concrete material.
- ANACAP cannot predict the final failure of the shear wall models due to its intentional modeling strategy

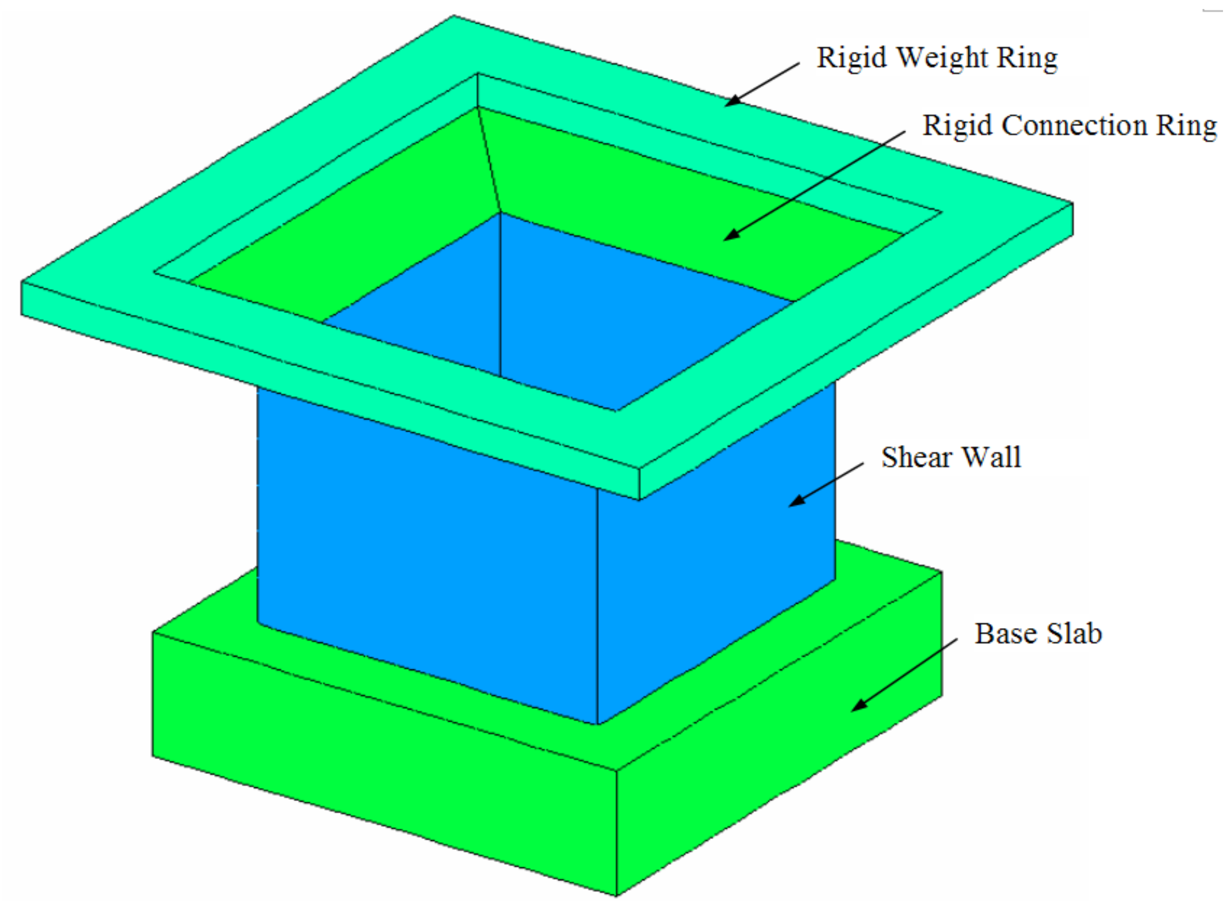


Cycle-By-Cycle Qx – Dx Relation for Diagonal Cross Loading

ANACAP Analysis of Shaking Table Test

- DT-B-02 specimen
  - The same FE shear wall model as for static analyses
- Idealization of the loading slab and the added weight
  - Great effort was made to minimize the number of elements so that ANACAP can run with acceptable execution time
- An explicit base slab to facilitate the application of the rocking and rolling motions
- Base slab, loading slab, and added weight parts were assumed rigid
- Analyzed consecutively with Runs 1, 2, 2’, 3, 3’, 4, 5, and 6
  - Damage state (stress and strain state) from prior runs was considered

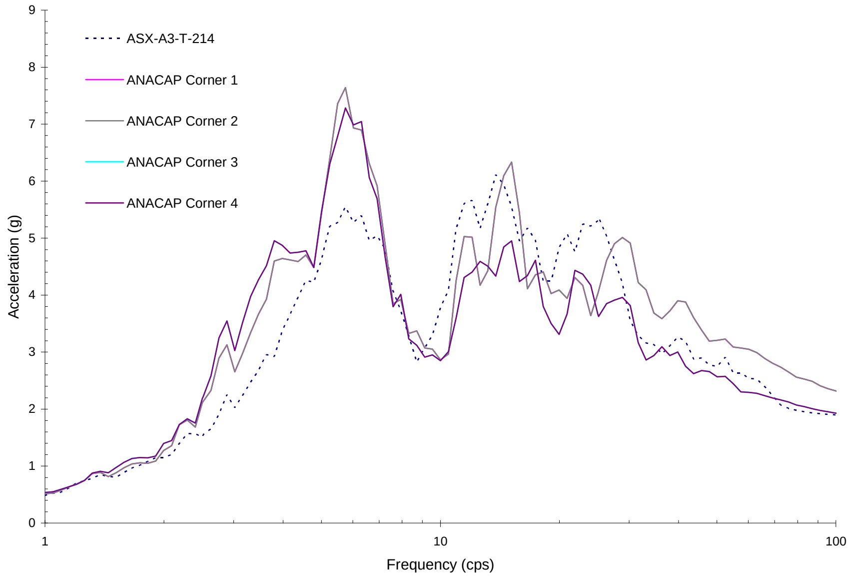
3D Models for DT-B-02 Specimen



United States Nuclear Regulatory Commission
Protecting People and the Environment

ANACAP Dynamic Analysis

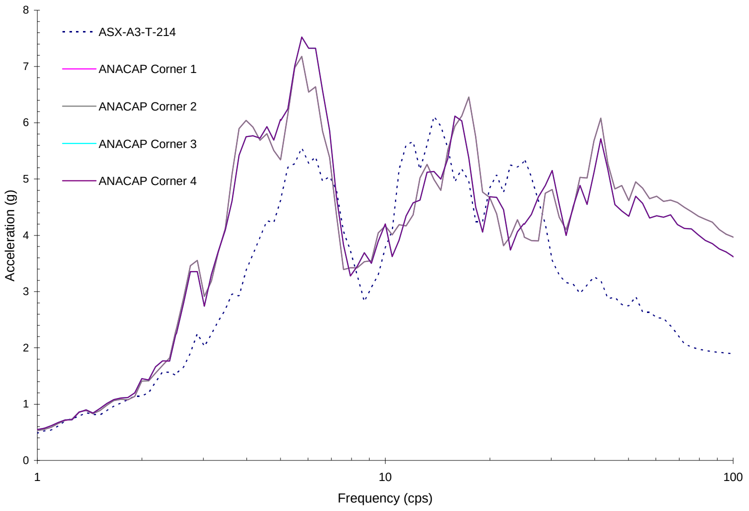
- Comparisons were made regarding response spectra, maximum shear forces, maximum total vertical forces, and hysteresis loops
- As an example, this figure shows a comparison of response spectra at the upper corners of the shear walls for Run 6
- Comparison of the maximum shear for Run 6
  - Less than 2% in the X direction
  - Lower than the test result by 21% in the Y direction
- Computed maximum vertical force appears to grossly exceed the test result by about 55%
- The accumulation of damage state by the ANACAP software agrees well with the test



Comparison of Response Spectra between ANACAP Analysis and the Test at Upper Corners of Shear Walls (Run 6, X Direction)

Effects of Prior Damage State

- Run 6 was re-analyzed without considering the prior damages (from intact state)
- The computed response spectra
  - agree well to the test results in the X-direction up to about 20 Hz; but much higher for frequencies above 30Hz
  - Broader than those of the test and the analytical response spectra with consideration of prior damage history
  - Captured the major frequency contents
- The maximum shear
  - Over-estimated by more than 50% in the X direction
  - Almost a perfect match in the Y direction
- The maximum vertical force grossly exceed the test by about 50%



Comparison of ANACAP Analysis without Considering Prior Damages for Run-6 in X-Direction at Upper Corners of Shear Walls and Measured Data

Conclusions

- ACI 349-01 methods for ultimate shear strength were found to be quite conservative, as would be expected
  - The level of conservatism is large for smaller aspect ratios and reduces as the aspect ratio increases
  - The interaction intensity also reduces the conservative margin
- ASCE 43-05 method for ultimate shear strength was found less conservative and more accurate than ACI 349-01 methods
- An adjustment factor for the ASCE 43-05 method was developed
  - As a linear function of the aspect ratio
  - The adjusted shear strength estimates compare very closely to the test results
  - ASCE 43-05 method should be used with caution for shear walls having aspect ratios greater than 0.9 (the largest aspect ratio in the tests was 0.87)
- No significant non-conservative bias is introduced by considering each direction independently as long as the bi-axial shear components are uncorrelated (e.g. using the 100-40-40 rule), for both the ACI 349-01 methods and the ASCE 43-05 method
- For calculation of the inelastic energy absorption factor
  - The Riddell-Newmark method conservatively bounds the test results
  - The point estimate method and spectral averaging generally over predict
  - The secant frequency method was the best for this specimen configuration and earthquake motion

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Conclusions (cont.)

- The computed base shear capacities by the ANACAP static analysis compare very well to the tests
- Reasonable agreement between the analysis results and the test data were achieved for the hysteresis loops and the shear force orbits
- ANACAP simulation generally captured the progressive degrading behavior of the shear wall
- The level of agreement for the in-structure response spectral peaks was about plus or minus 30% in the horizontal comparisons and about plus or minus 50% in the vertical comparisons
- The base shears predicted by ANACAP are mostly higher than test results, with a few cases under-predicted by only about 3 to 8%
- The response differences between including and ignoring prior damage history demonstrated the importance of appropriately accounting for the degraded condition in the seismic analysis of shear walls
- The JNES/NUPEC cyclic and shaking table test data can be used as a benchmark for future validations of the adequacy of other alternative analytical methods or computer programs for the seismic response analysis of NPP low-rise shear wall structures