

# **PAULAY & PARK SYMPOSIUM**

**DOES CAPACITY DESIGN DO THE JOB?  
AN EXAMINATION OF HIGHER MODE  
EFFECTS IN CANTILEVER WALLS**

**Nigel Priestley**

# INTRODUCTION

## HIGHER MODES IN SEISMIC DESIGN



**EQUIVALENT LATERAL  
FORCE PROCEDURE**

**(ONLY FIRST MODE)**

**MODAL RESPONSE  
SPECTRUM PROCEDURE**

**(ALL SIGNIFICANT MODES)**

# CANTILEVER WALL DESIGN FORCES

## Equivalent Lateral Force Approach

**PLASTIC HINGES** - Flexural Strength from Design Lateral Forces

**OTHER REGIONS** - No Hinges, No Shear Failure. Forces Amplified for:

- Flexural Overstrength:  $f^o$
- Higher Mode Effects:  $w$

$$S_R = f^o w S_E$$

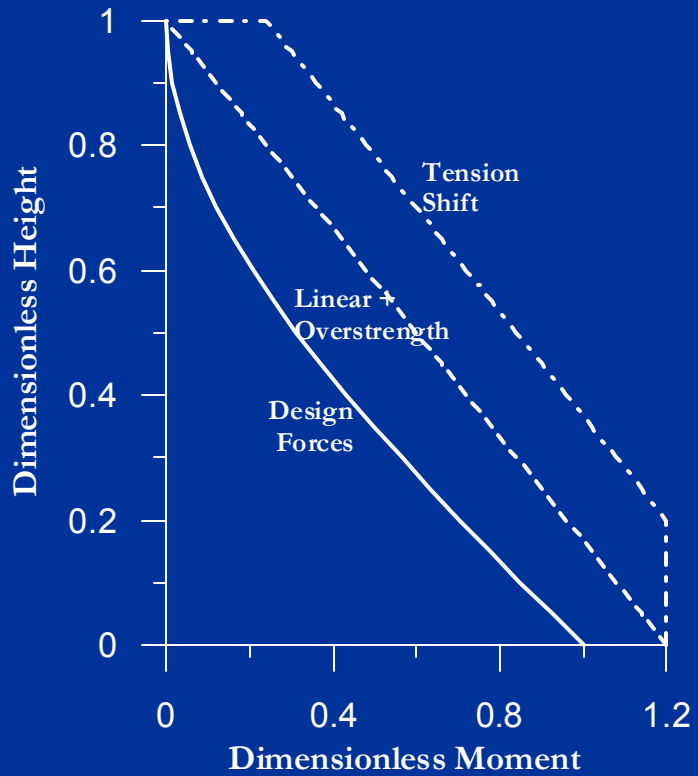
$S_R$  = Required Strength

$S_E$  = Strength from Design Lateral Forces

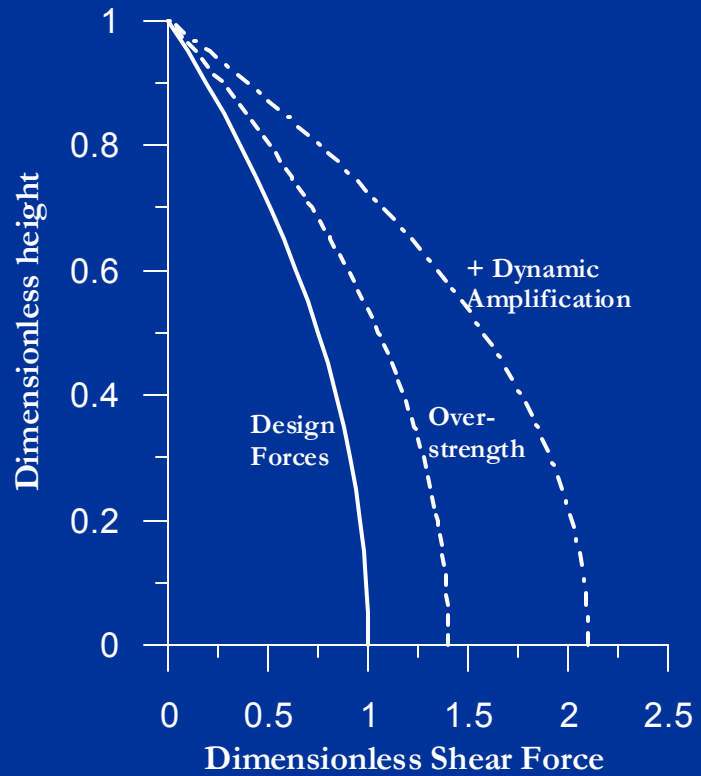
**for Shear Forces:**

$$w = 0.9 + n/10 \quad (\text{for } n < 6)$$

$$w = 1.3 + n/30 \quad (\text{for } 6 < n < 15) \quad (\text{max} = 1.8)$$



(a) Moment Profiles



(b) Shear Force Profiles

**DYNAMIC AMPLIFICATION OF DESIGN FORCES IN  
CANTILEVER WALL DESIGN (ELF PROCEDURE)**

# MODAL RESPONSE SPECTRUM PROCEDURE

## Elastic Forces and Displacement

$$F_{ie} = \sqrt{\sum_{i,m=1}^N F_{im}^2}, \quad M_{ie} = \sqrt{\sum_{i,m=1}^N M_{im}^2}, \quad V_{ie} = \sqrt{\sum_{i,m=1}^N V_{im}^2}, \quad \text{and} \quad \Delta_{ie} = \sqrt{\sum_{i,m=1}^N \Delta_{im}^2}$$

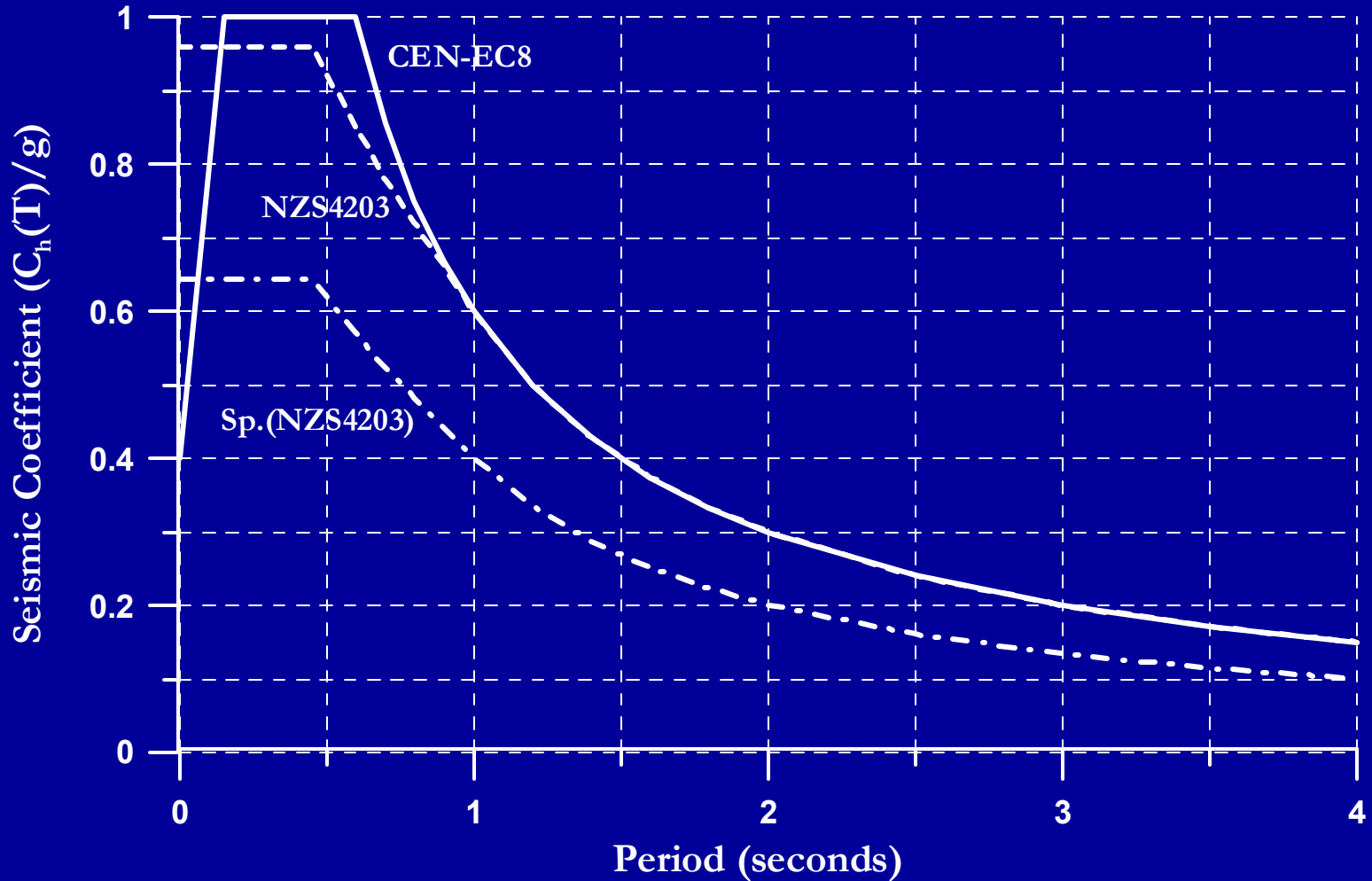
## Design Forces and Displacement

$$F_{iD} = \frac{F_{ie}}{q}, \quad M_{iD} = \frac{M_{ie}}{q}, \quad V_{iD} = \frac{V_{ie}}{q}, \quad \text{and} \quad \Delta_{iD} = \Delta_{ie}$$

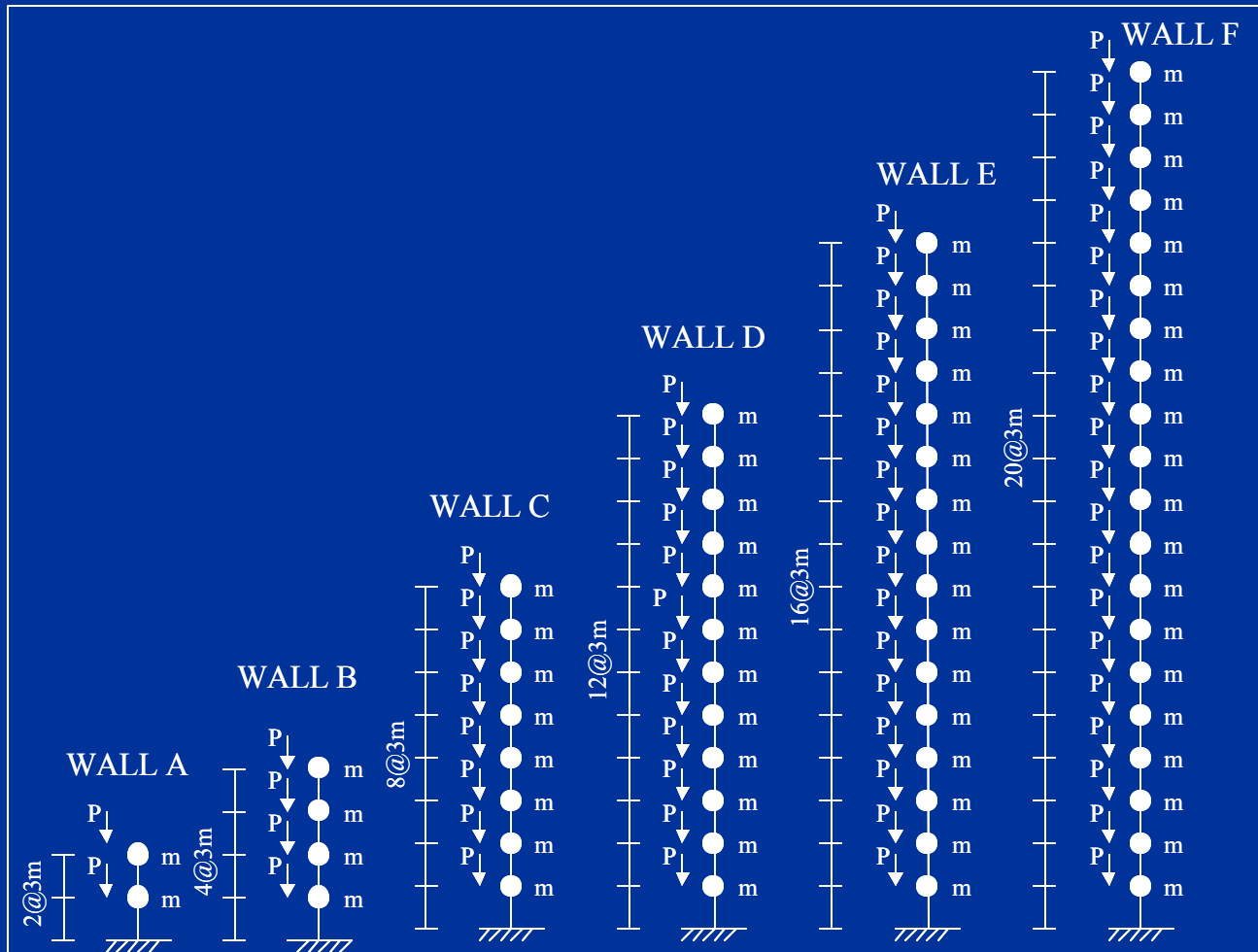
Note: If seismic intensity exceeds design level, elastic forces increase in proportion, but the base moment capacity is not influenced. Hence the effective behaviour factor  $q$  increases in proportion. Design forces throughout the wall are thus unchanged.

# DESIGN STUDIES

- **Six walls designed to EC8, 0.4g PGA, Subsoil Class B**
- **Displacement-based design for approximately 0.024 drift**
- **Inelastic Time-history analysis using spectrum compatible records**
- **Earthquake records scaled to 50%, 100%, 150% and 200% of design intensity**
- **Dynamic Amplification of Moment and Shear Force of interest**



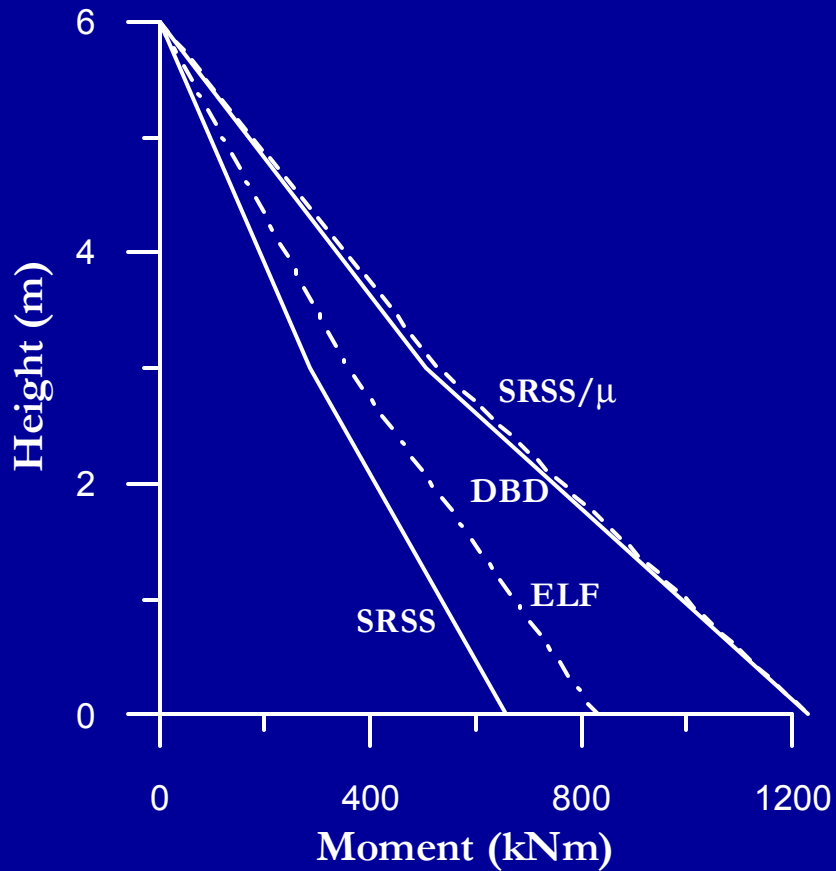
**EC8 Spectrum for 0.4g & NZS4203 (elastic) for  $Z = 1.2$**



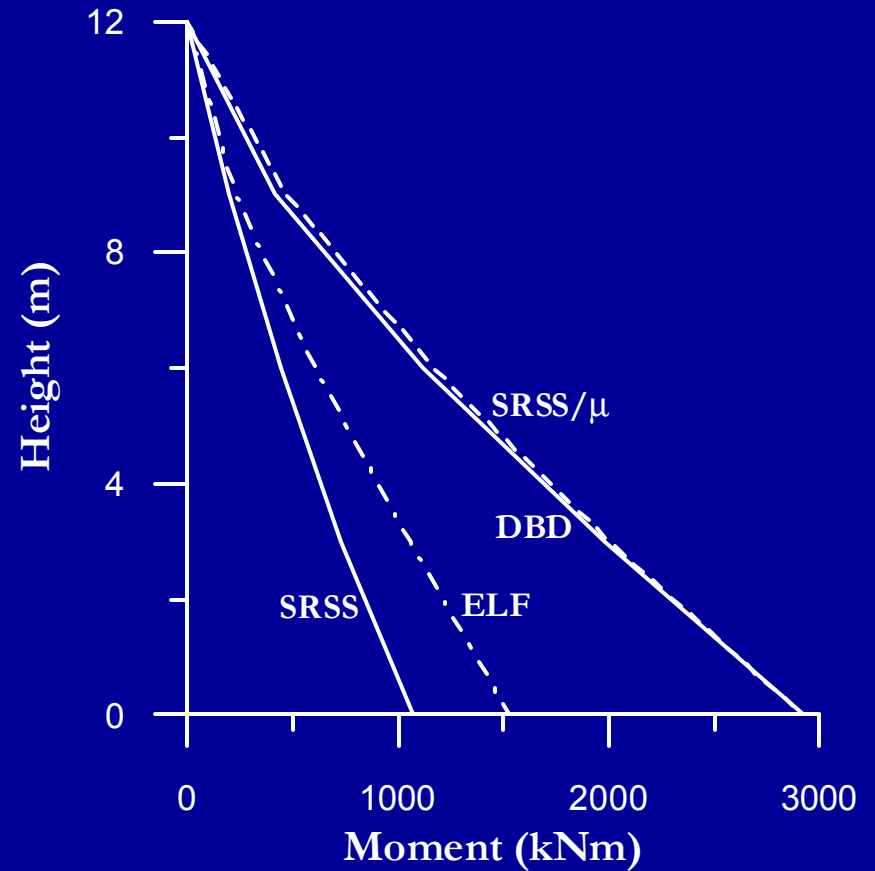
## CANTILEVER WALLS ANALYSED

## DETAILS FOR CANTILEVER WALL STUDY

Wall	b (m)	$l_w$ (m)	$r_l$	$d_b$ (mm)	$l_p$ (m)	$m_D$	$m_f$	$T_{eff}$ (sec)	$V_b$ (kN)	$M_b$ (kNm)
A	0.20	2.0	0.0046	14	0.58	6.4	20.6	1.2	242	1232
B	0.20	2.5	0.0080	14	0.86	3.4	12.6	1.8	312	2917
C	0.20	3.3	0.0162	20	1.49	1.9	6.0	2.6	446	8114
D	0.25	4.0	0.0172	28	2.22	1.3	2.7	3.1	590	16222
E	0.25	5.0	0.0161	24	2.83	1.2	2.2	3.7	664	24372
F	0.30	5.6	0.0177	28	3.52	1.0	1.0	3.9	830	38739

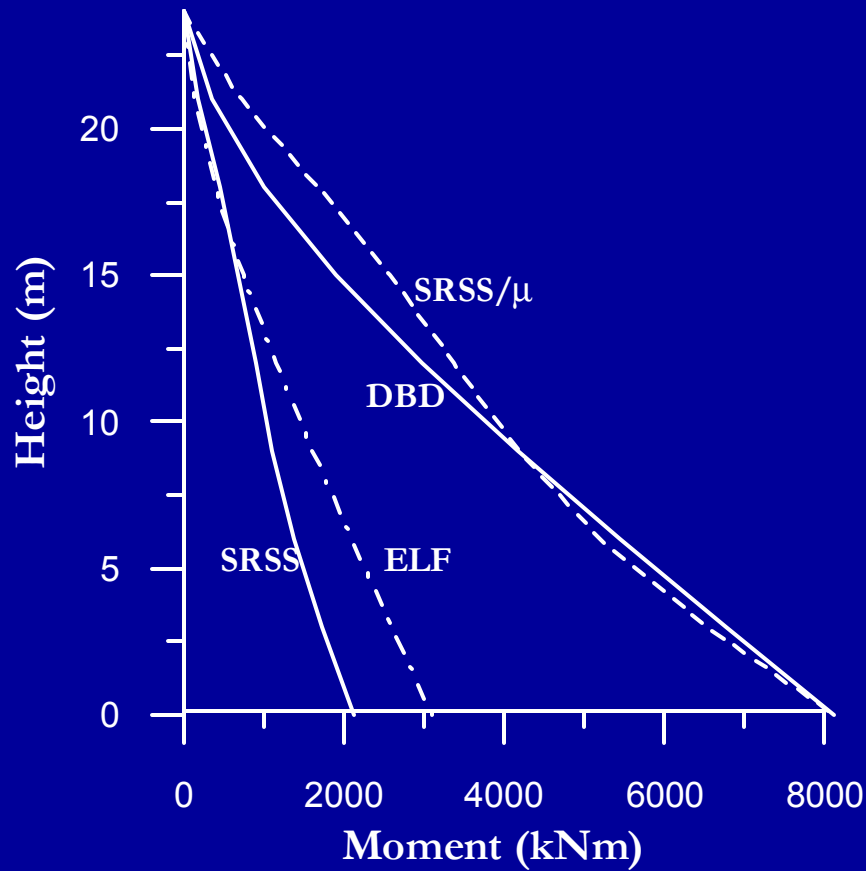


(a) Two-storey Wall

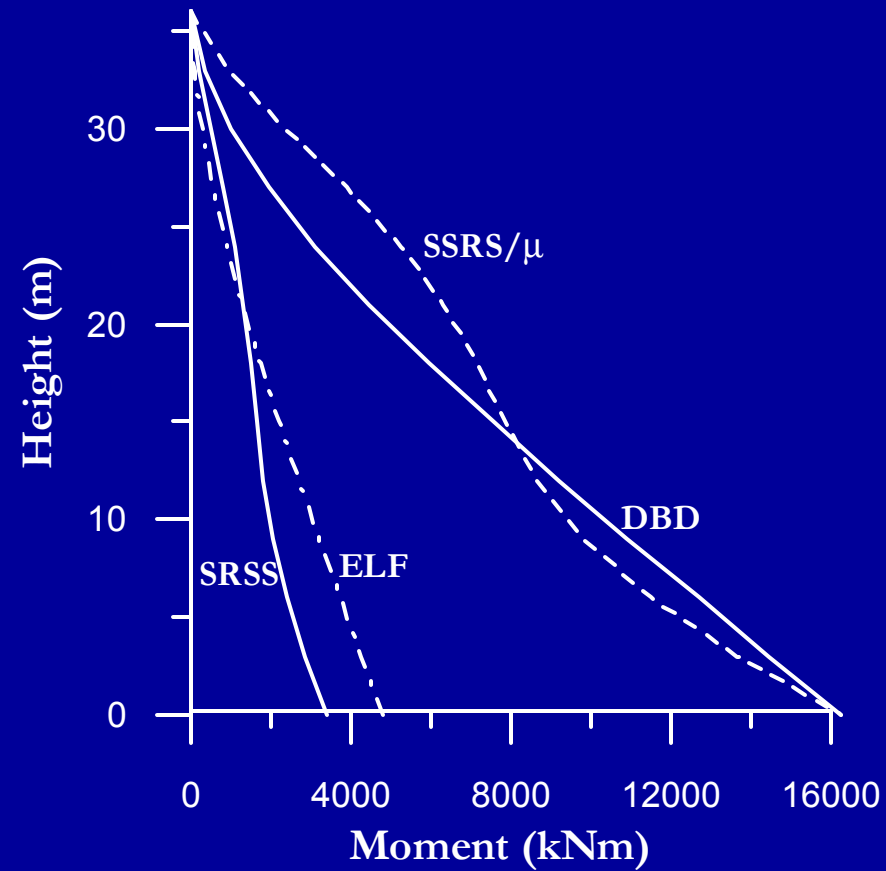


(b) Four-Storey Wall

**Wall Design Moments from Different Procedures**

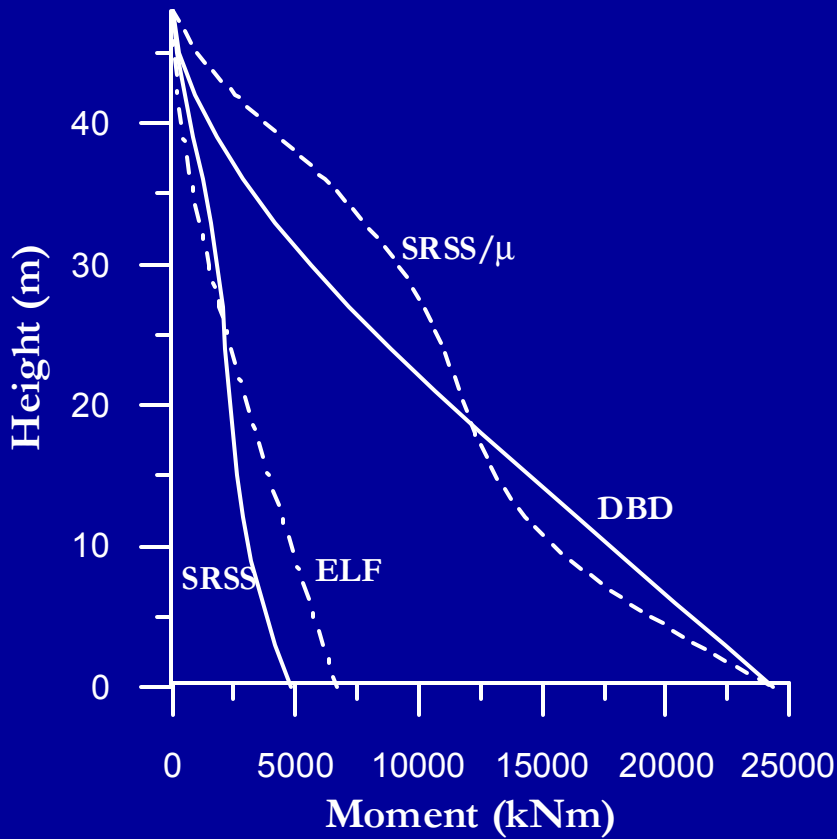


(c) Eight-Storey Wall

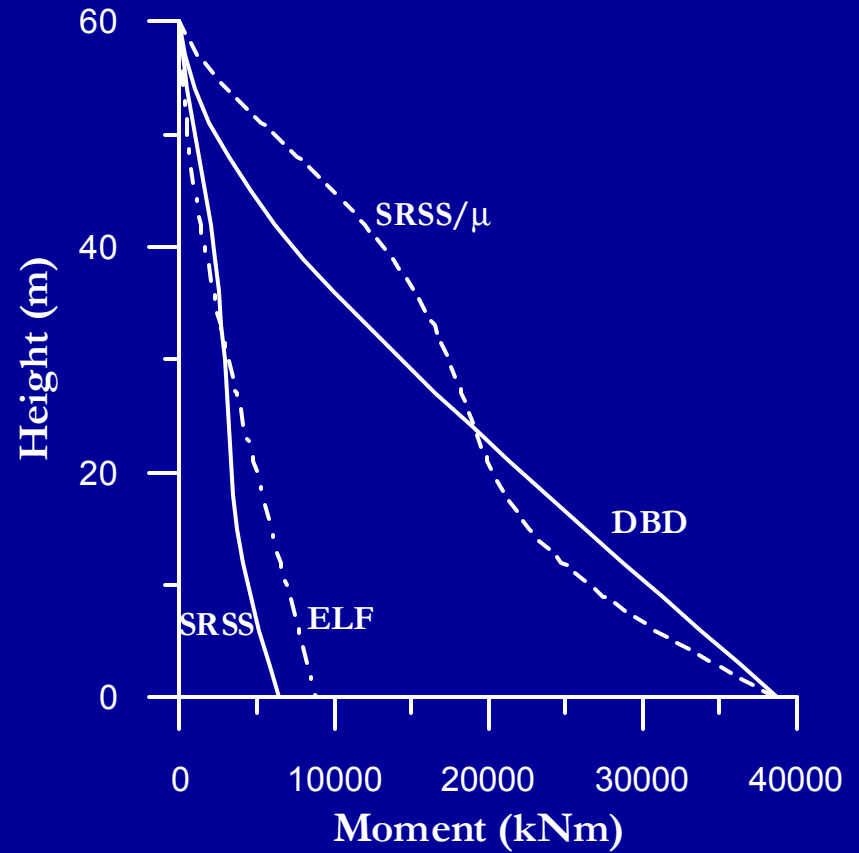


(f) Twelve-Storey Wall

**Wall Design Moments from Different Procedures**

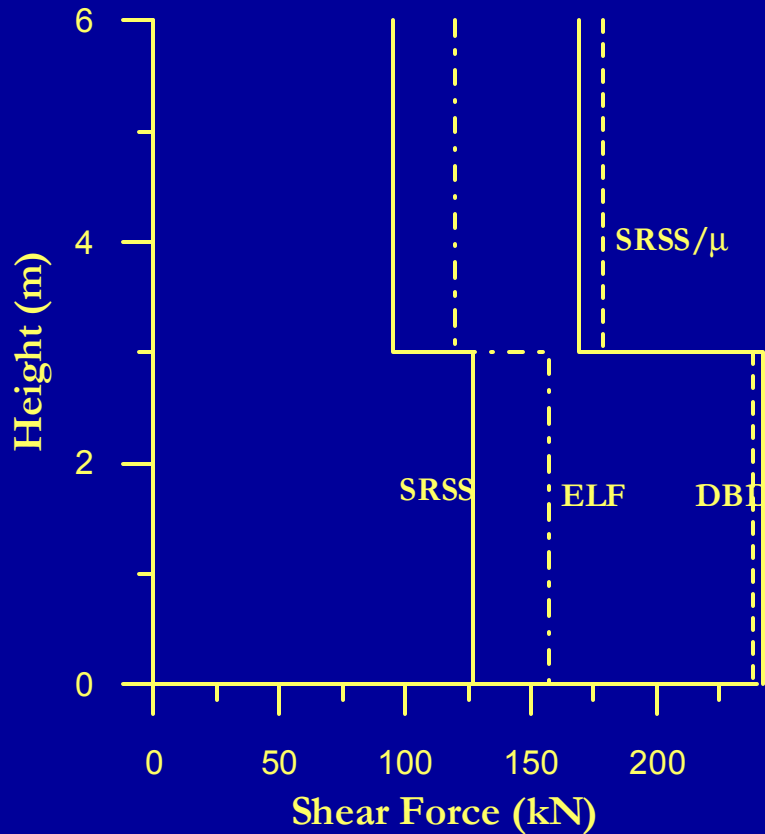


(e) Sixteen-Storey Wall

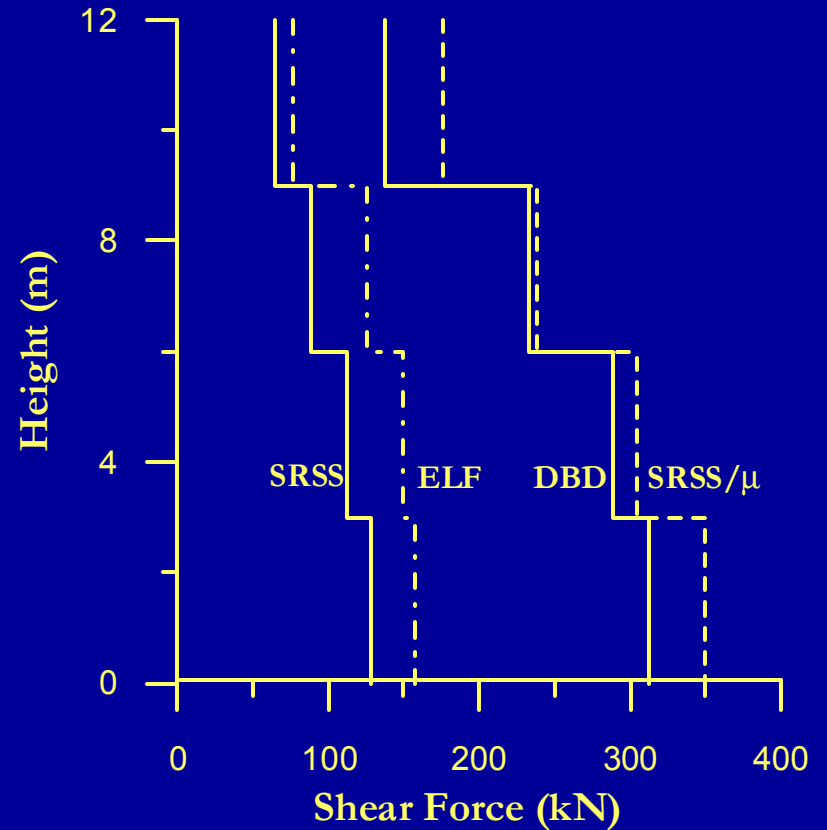


(f) Twenty-Storey Wall

**Wall Design Moments from Different Procedures**



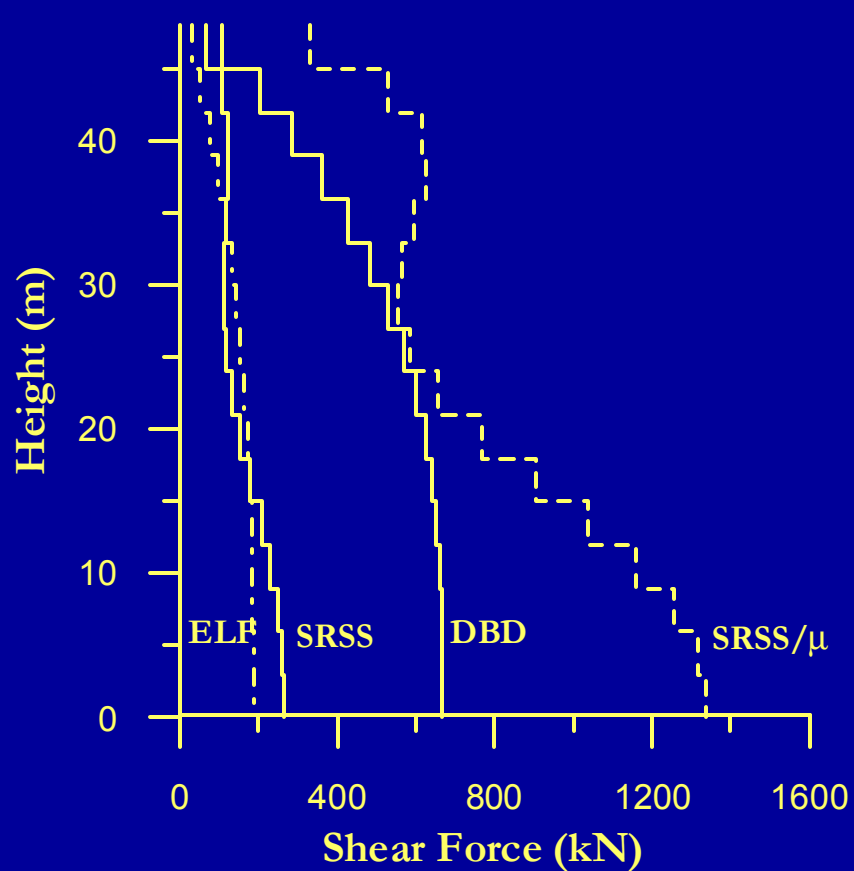
(a) Two-Storey Wall



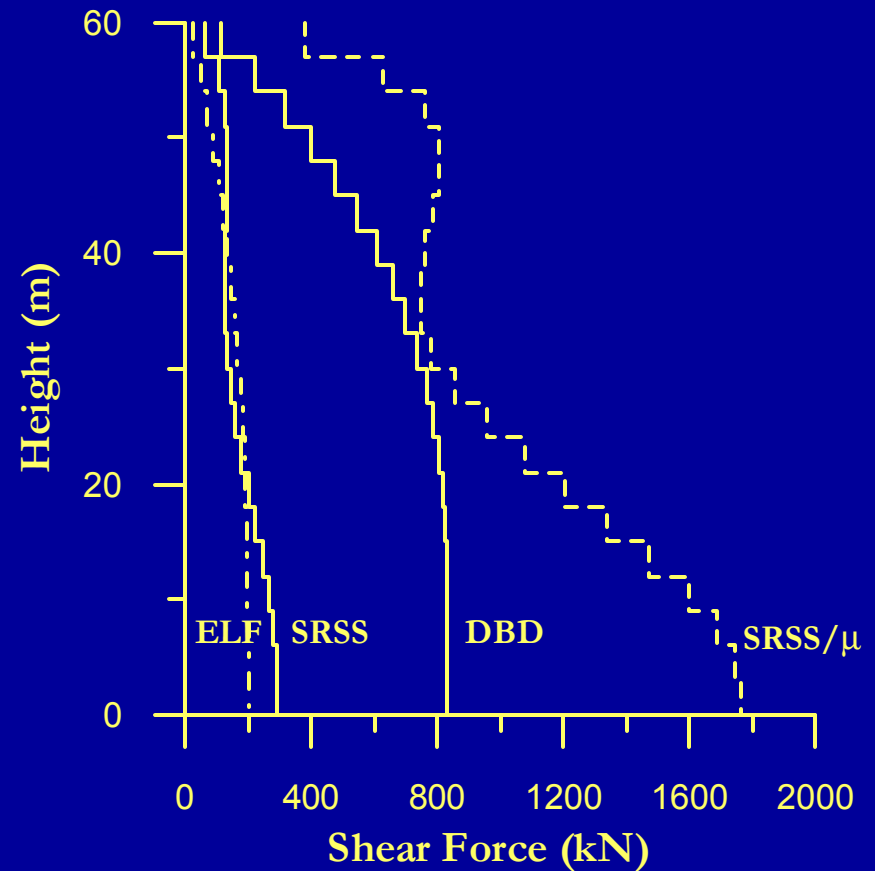
(b) Four-Storey Wall

## Wall Design Shears from Different Procedures





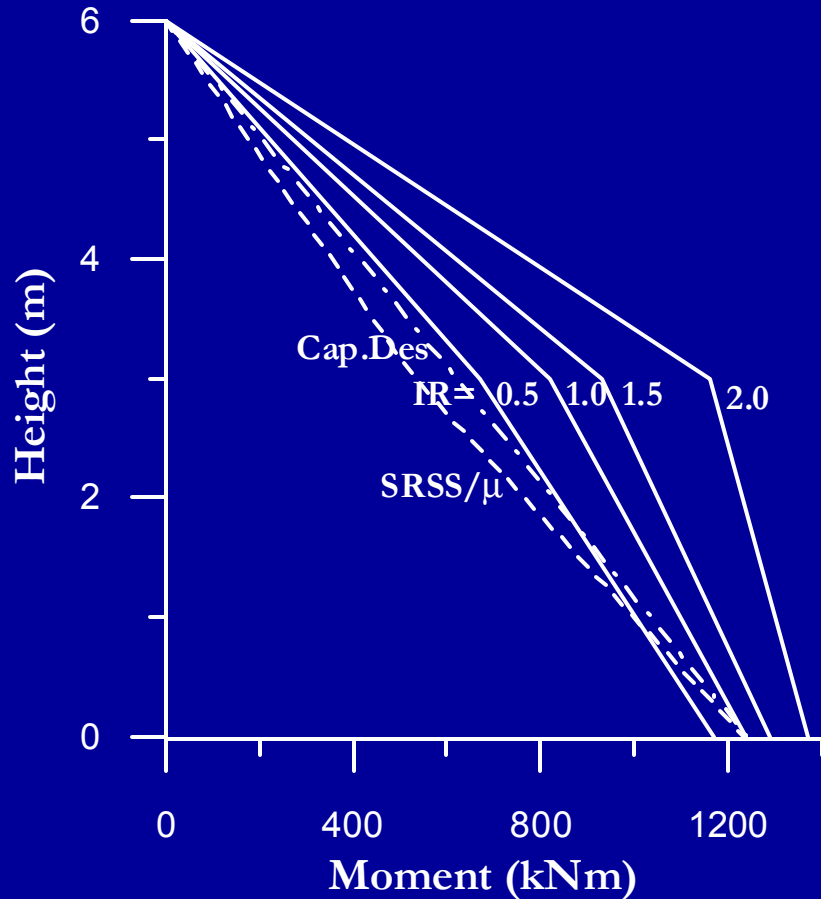
(e) Sixteen-Storey Wall



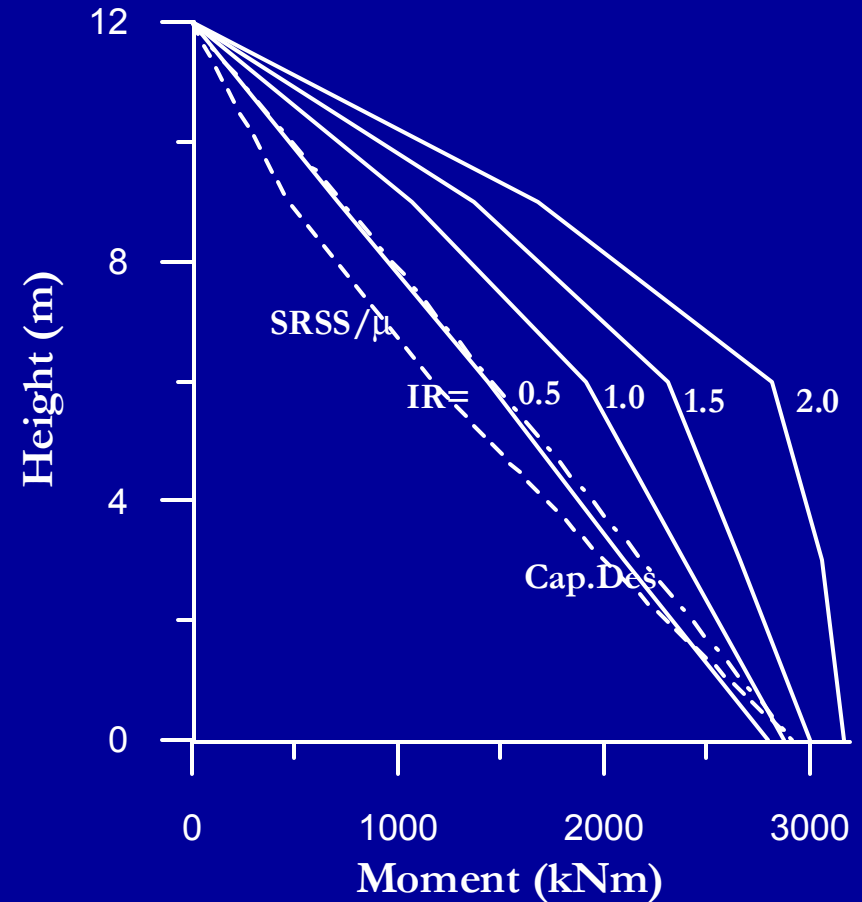
(f) Twenty-Storey Wall

## Wall Design Shears from Different Procedures

**RESULTS OF TIME-HISTORY  
ANALYSES**

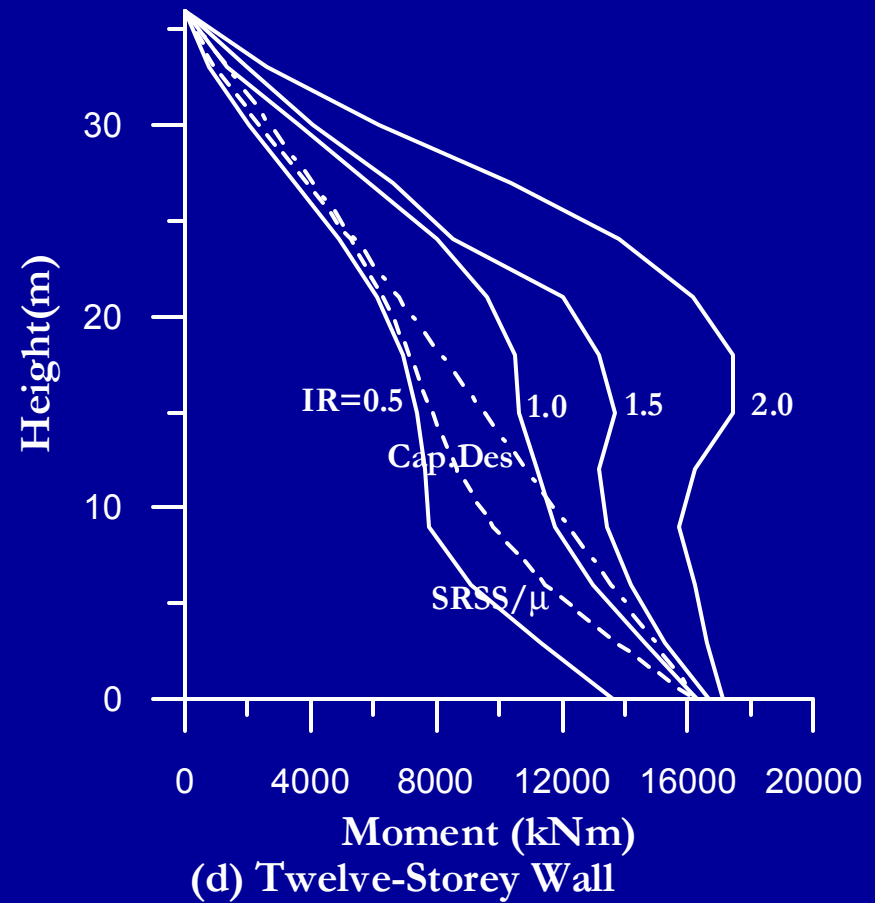
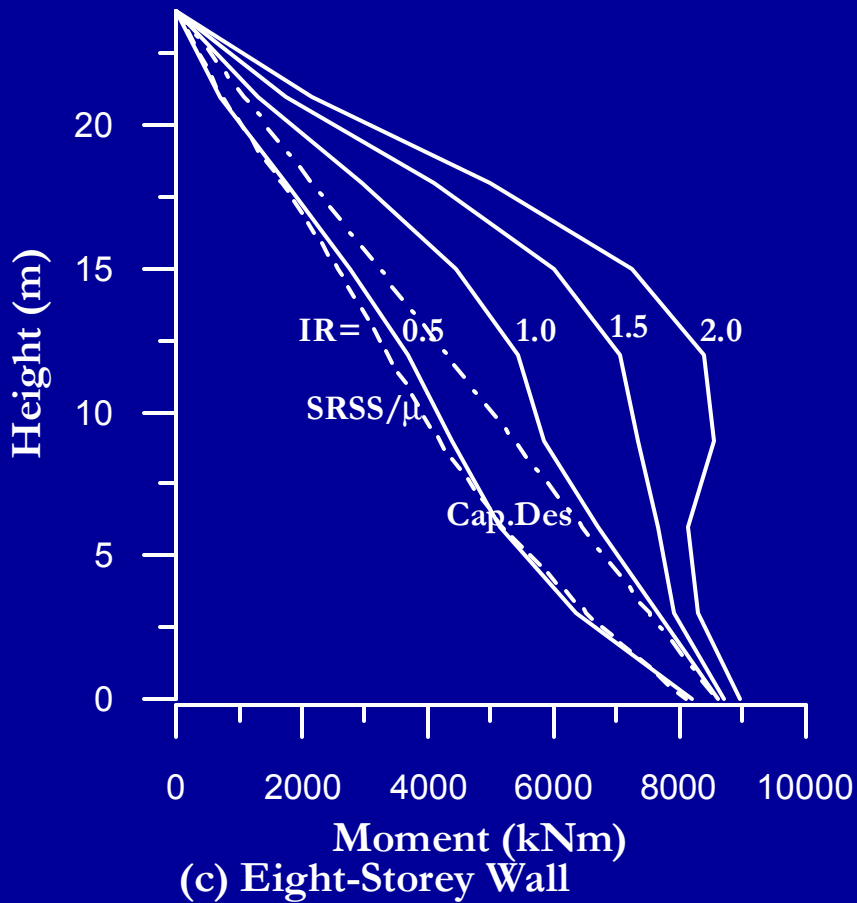


(a) Two-Storey Wall

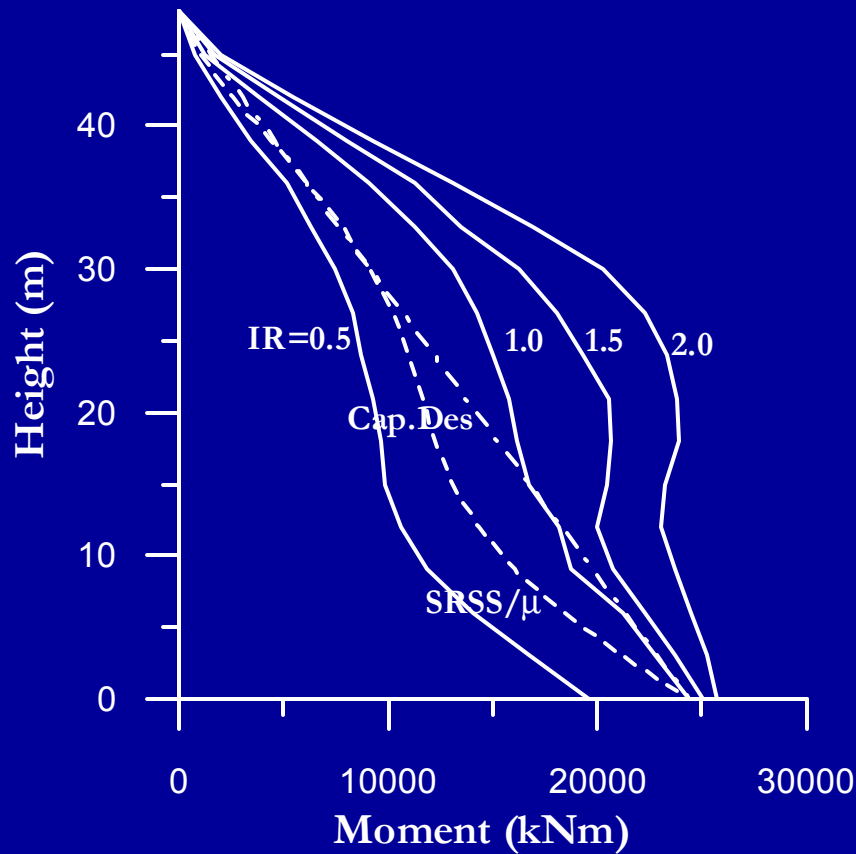


(b) Four-Storey Wall

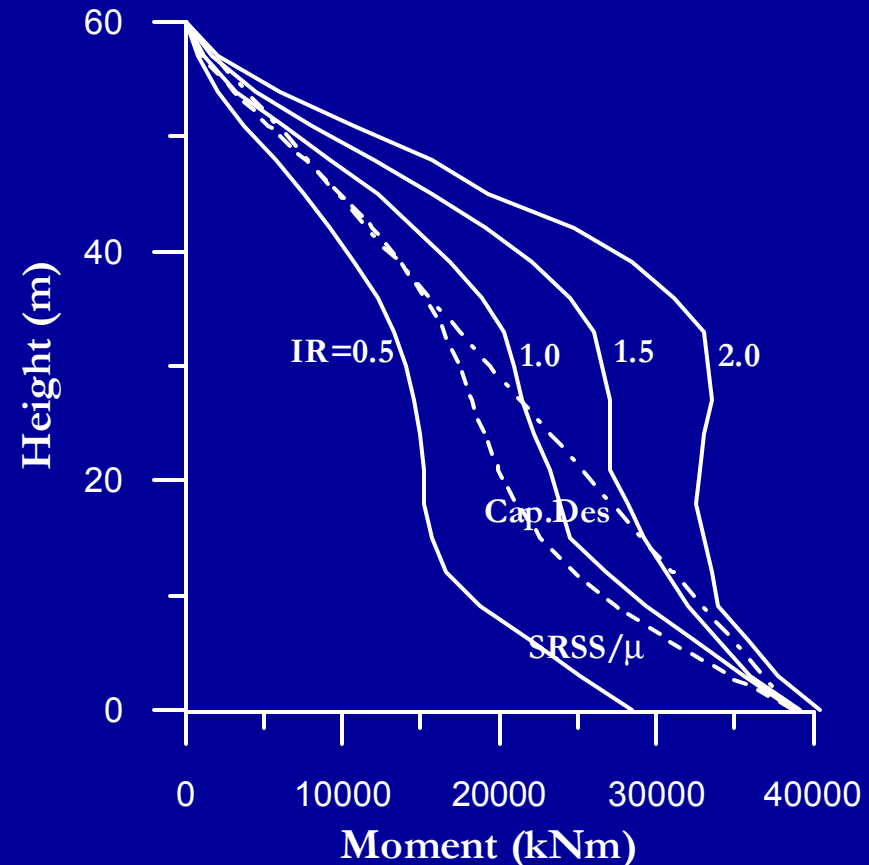
**Capacity Design Moments and Time-History Results for Different Seismic Intensity Ratios (IR=1=Design Intensity)**



**Capacity Design Moments and Time History Results for Different Seismic Intensity Ratios (IR=1=Design Intensity)**

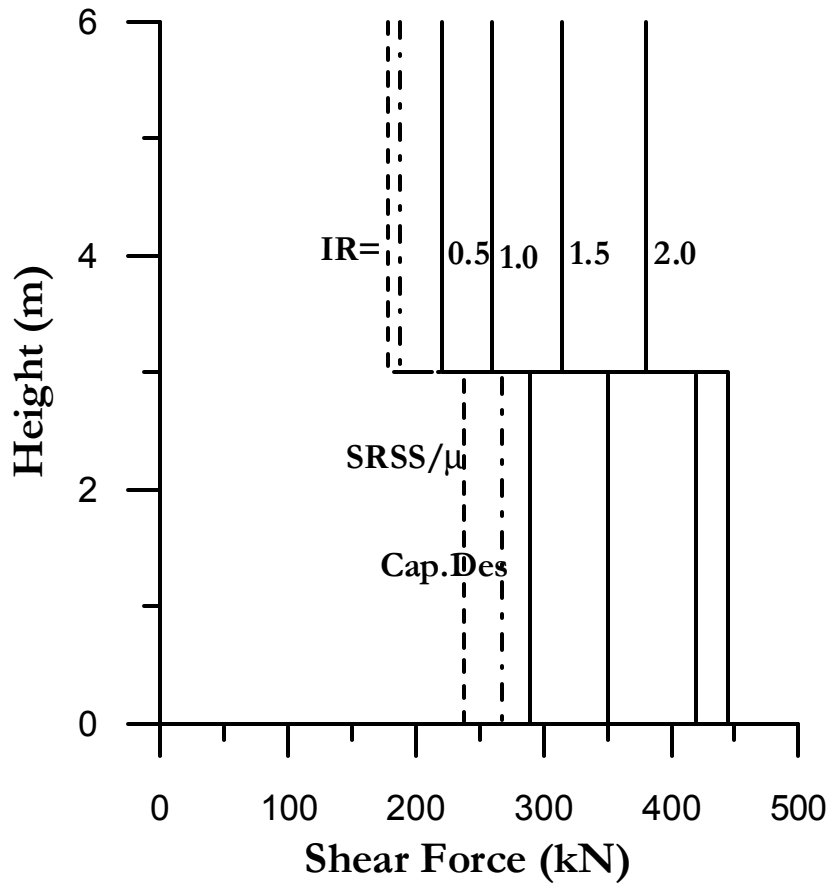


(e) Sixteen-Storey Wall

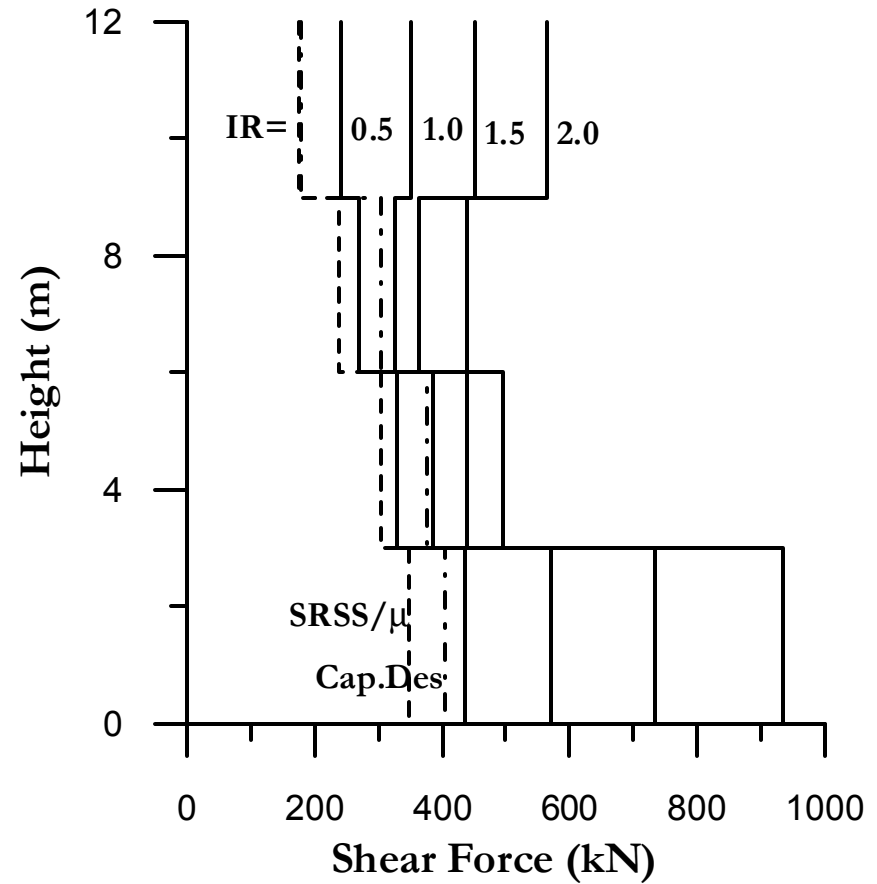


(f) Twenty-Storey Wall

**Capacity Design Moments and Time History Results for Different Seismic Intensity Ratios (IR=1=Design Intensity)**

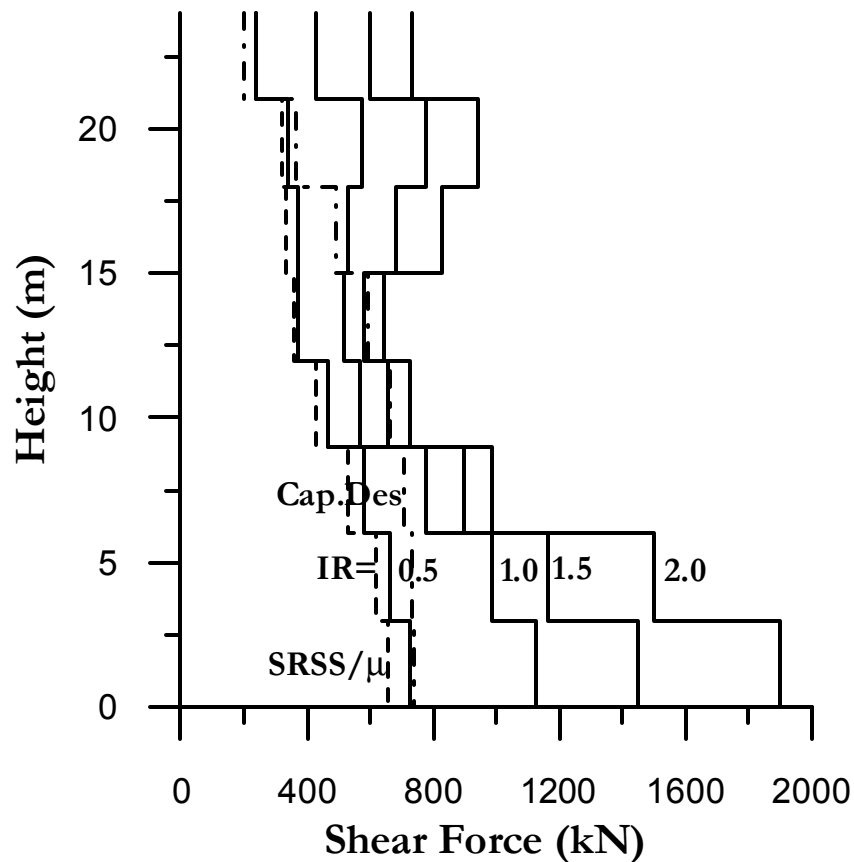


(a) Two-Storey Wall

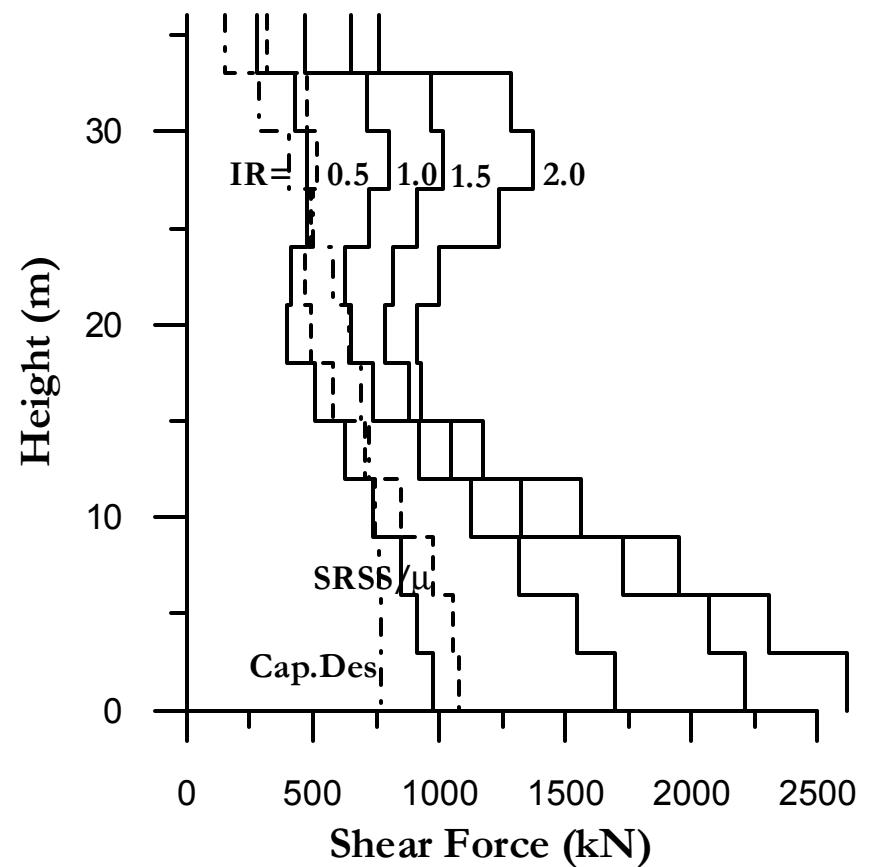


(b) Four-Storey Wall

**Capacity Design Shears and Time History Results for Different Seismic Intensity Ratios (IR=1=Design Intensity)**

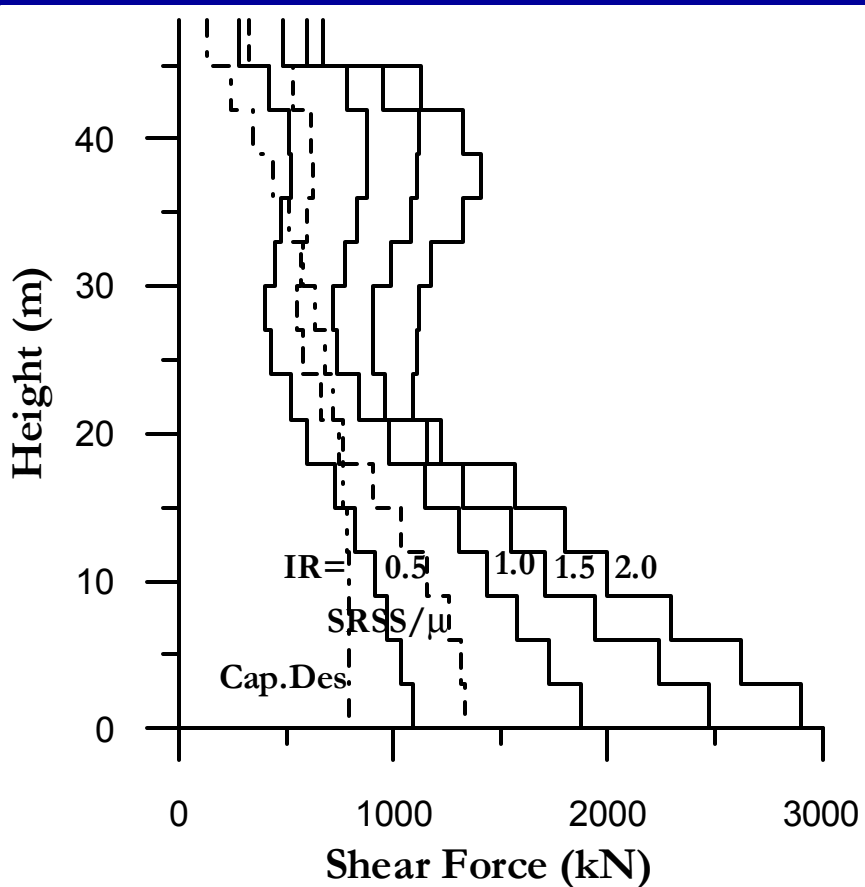


(c) Eight-Storey Wall

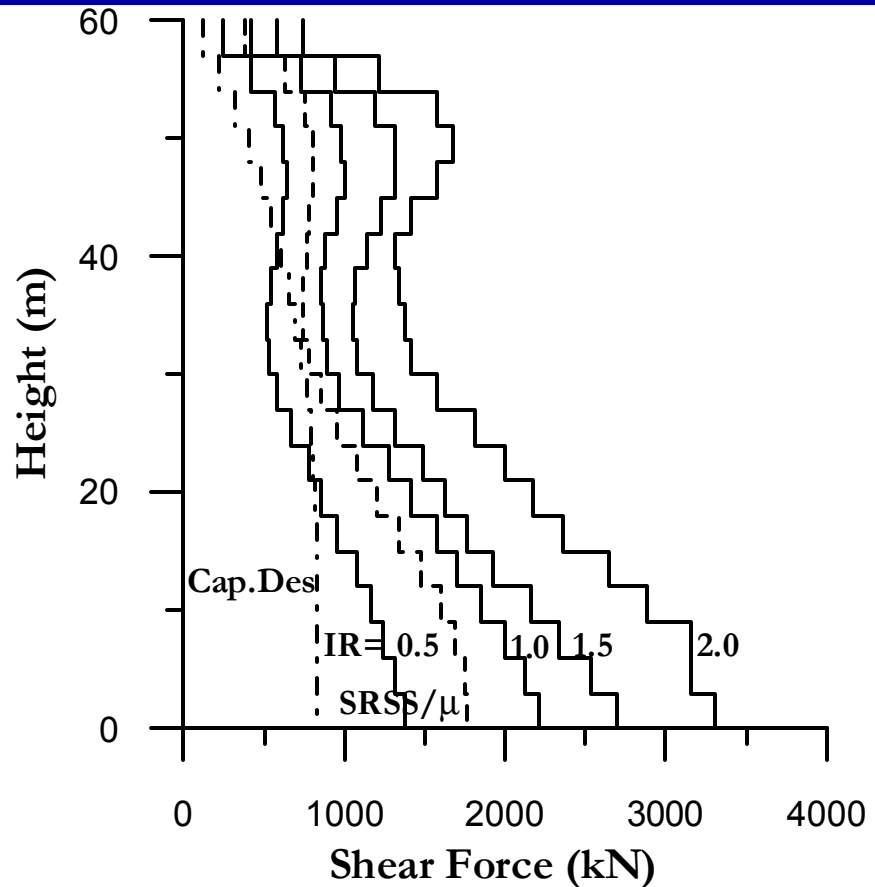


(d) Twelve-Storey Wall

**Capacity Design Shears and Time History Results for Different Seismic Intensity Ratios (IR=1=Design Intensity)**



(e) Sixteen-Storey Wall



(f) Twenty-Storey Wall

**Capacity Design Shears and Time-History Results for Different Seismic Intensity Ratios (IR=1=Design Intensity)**

# CONCLUSIONS FROM TIME-HISTORY ANALYSES

- **Results are Intensity-Dependent (i.e. Ductility-Dependent)**
- **Modal Response Spectra and ELF Approaches Underestimate Moments above Base, and Shear Forces over full height.**
- **Results suggest that a simple modification to the modal superposition approach could predict moments and shear forces**
- **Shape of Shear Force Profile Similar to SSRS/m for low Intensity Ratios (i.e. for low ductilities).**

# MODIFIED MODAL SUPERPOSITION (MMS)

Extension to Method suggested by Eibl and Keintzel, 1988

## SHEAR FORCE PROFILES

$$V_i = (V_{1i}^2 + V_{2Ei}^2 + V_{3Ei}^2 + \dots)^{0.5}$$

$V_{1i}$  = Inelastic first-mode shear force at level  $i$  (from DBD forces) or elastic shear force, if lower

$V_{2Ei}$  (etc) = elastic 2nd (etc) mode shear force at level  $i$

**THUS FORCE REDUCTION FOR DUCTILITY IS ONLY APPLIED TO FIRST MODE**

# MODIFIED MODAL SUPERPOSITION (MMS)

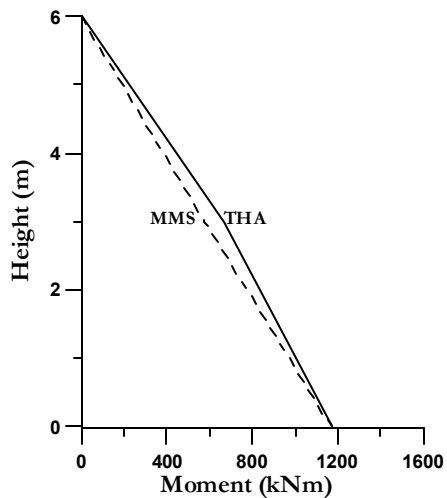
## MOMENT PROFILES

$$M_i = 1.1 \times (M_{1i}^2 + M_{2Ei}^2 + M_{3Ei}^2 + \dots)^{0.5}$$

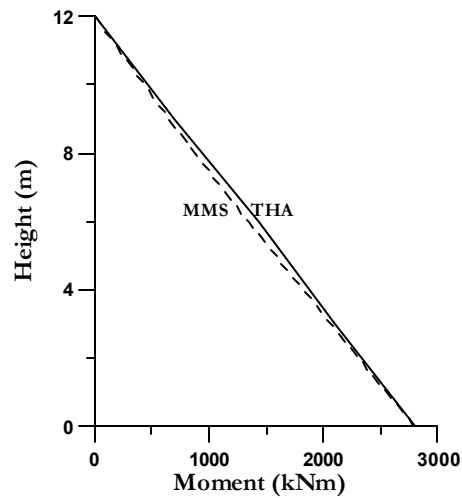
$M_{1i}$  = Inelastic first-mode moment at level  $i$  from DBD

$M_{2Ei}$  (etc) = elastic 2nd (etc) mode moment at level  $i$

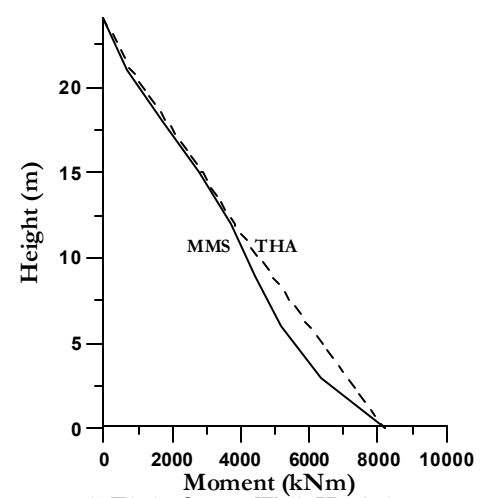
**NOTE: EQN APPLIES ONLY OVER TOP HALF OF WALL. LINEAR PROFILE FROM MIDHEIGHT TO WALL BASE MOMENT**



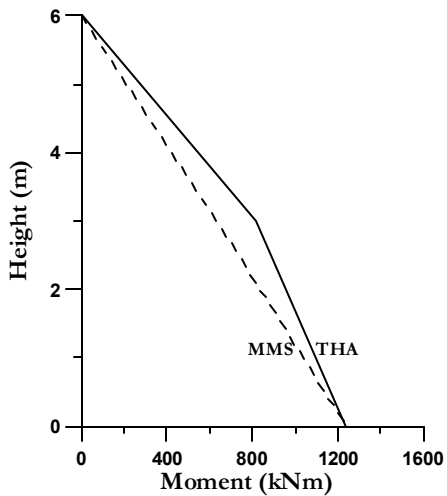
(a) Two-Storey Wall, IR=0.5



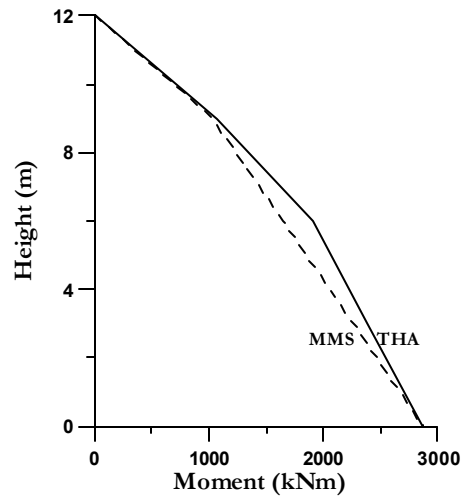
(e) Four-Storey Wall, IR=0.5



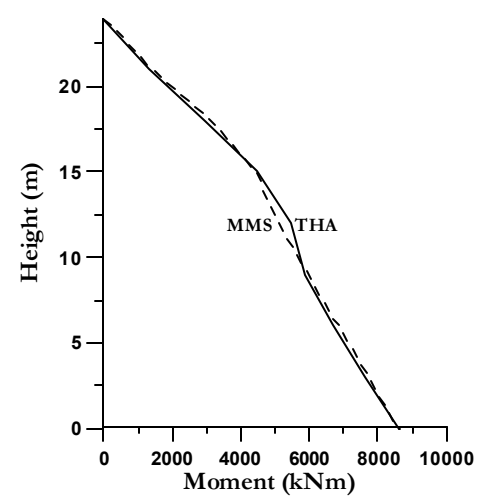
(i) Eight-Storey Wall, IR=0.5



(b) Two-Storey Wall, IR=1.0

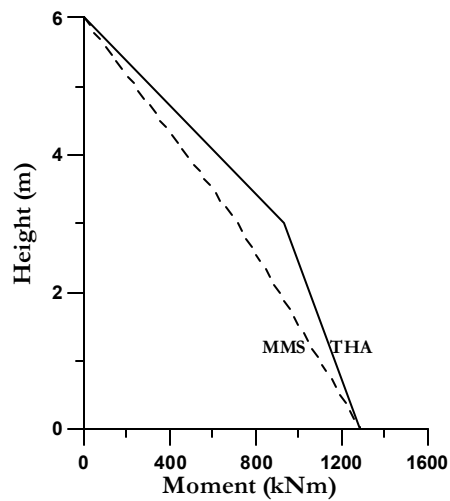


(f) Four-Storey Wall, IR=1.0

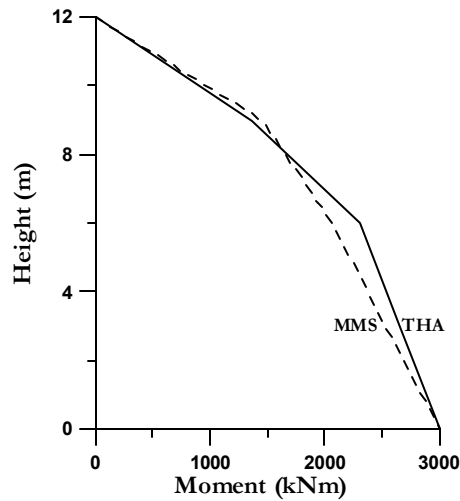


(j) Eight-Storey Wall, IR=1.0

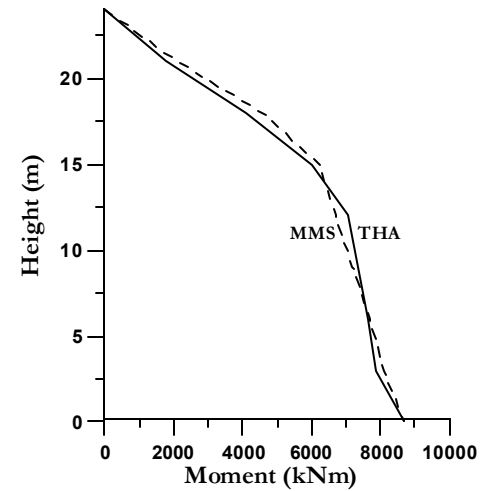
**MMS Moment Envelopes Compared with Time History Results for Different Seismic Intensities (IR=1=Design)**



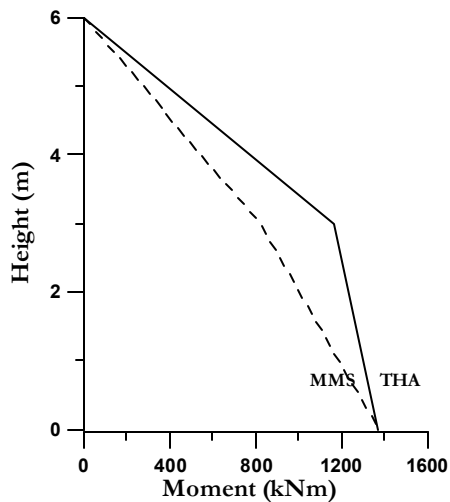
(c) Two-Storey Wall, IR=1.5



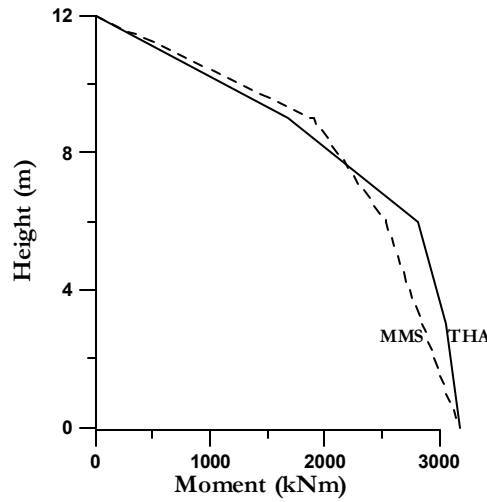
(g) Four-Storey Wall, IR=1.5



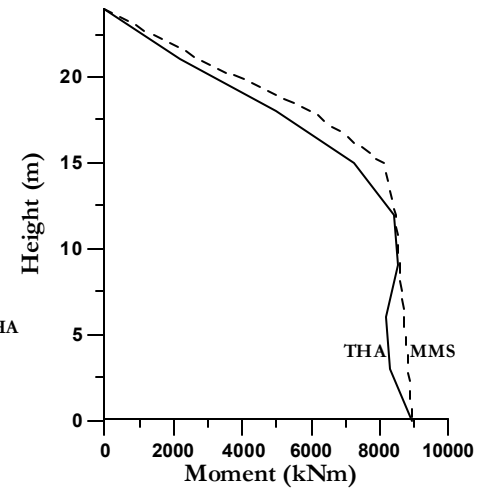
(k) Eight-Storey Wall, IR=1.5



(d) Two-Storey Wall, IR=2.0

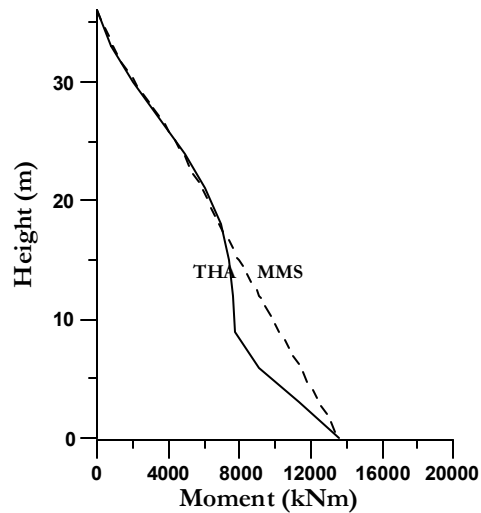


(h) Four-Storey Wall, IR=2.0

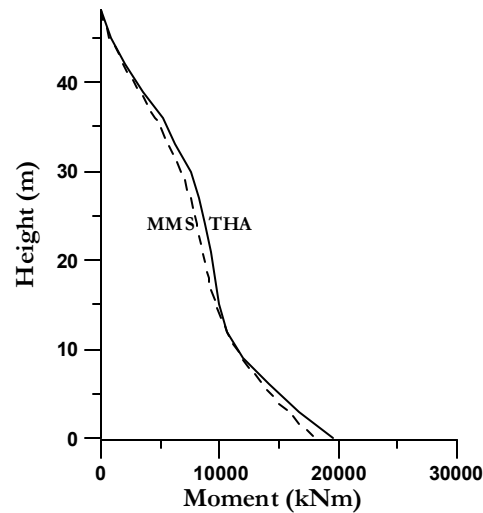


(l) Eight-Storey Wall, IR=2.0

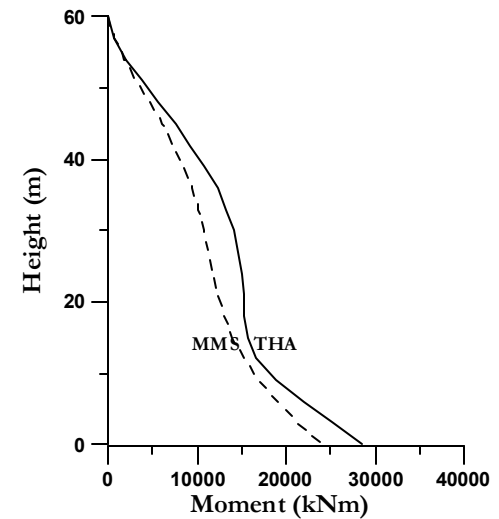
**MMS Moment Envelopes Compared with Time History Results for Different Seismic Intensities (IR=1=Design)**



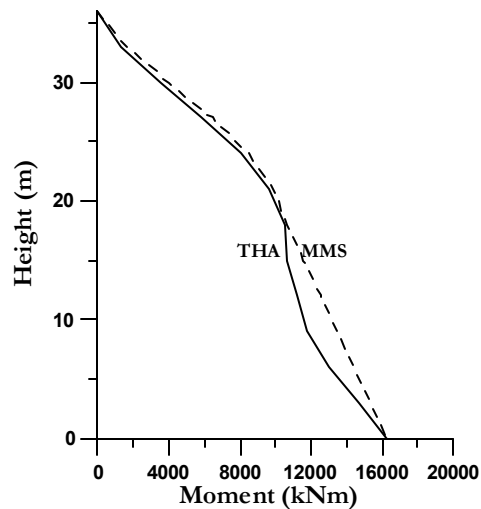
(m) Twelve-Storey Wall, IR=0.5



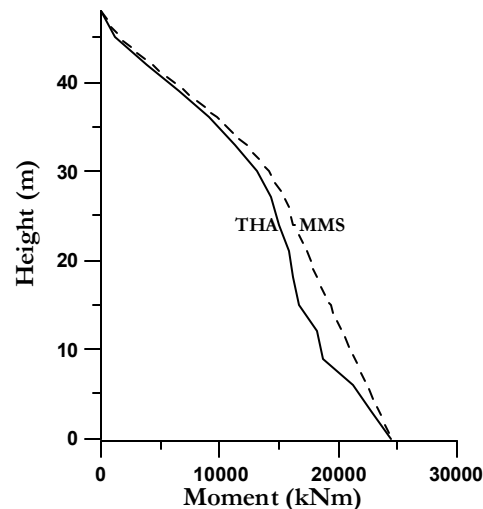
(q) Sixteen-Storey Wall, IR=0.5



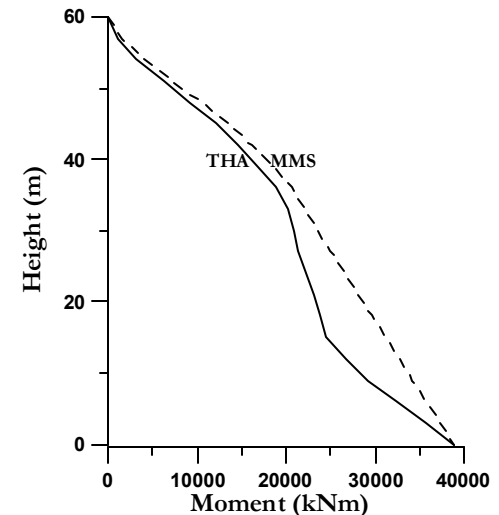
(u) Twenty-Storey Wall, IR=0.5



(n) Twelve-Storey Wall, IR=1.0

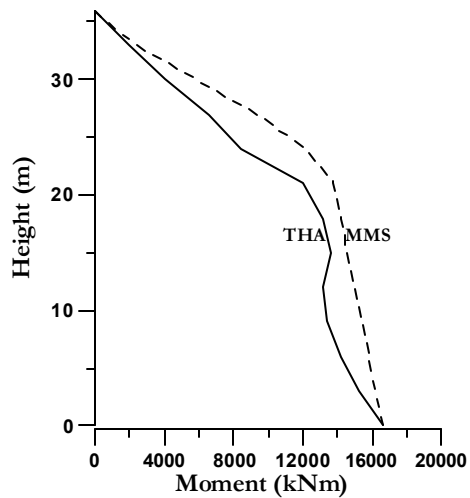


(r) Sixteen-Storey Wall, IR=1.0

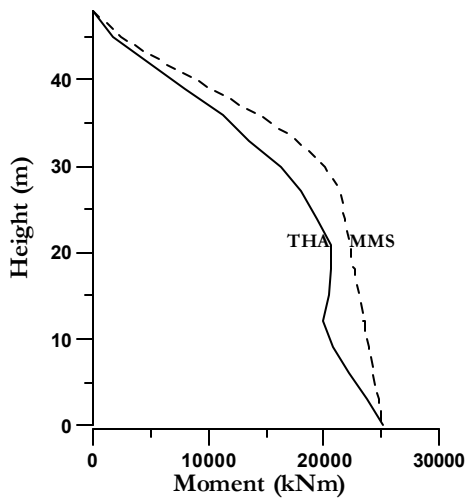


(v) Twenty-Storey Wall, IR=1.0

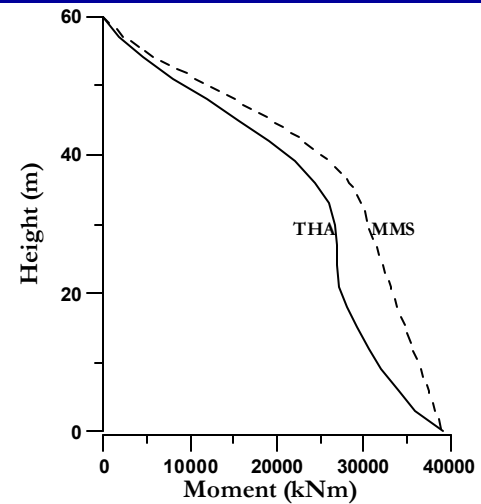
**MMS Moment Envelopes Compared with Time History Results for Different Seismic Intensities (IR=1=Design)**



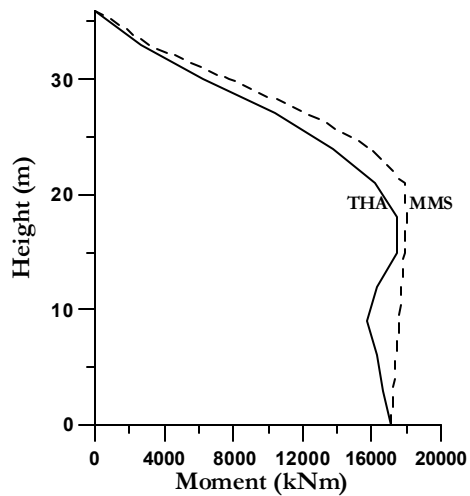
(o) Twelve-Storey Wall, IR=1.5



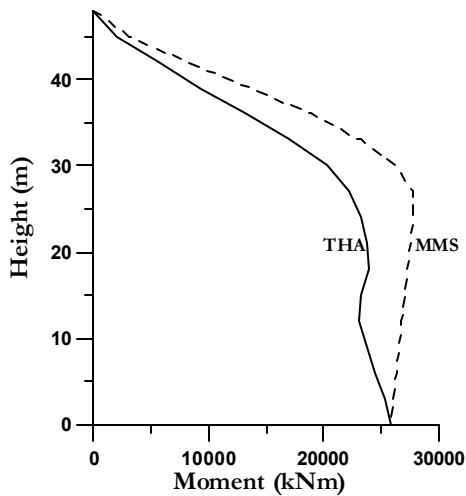
(s) Sixteen-Storey Wall, IR=1.5



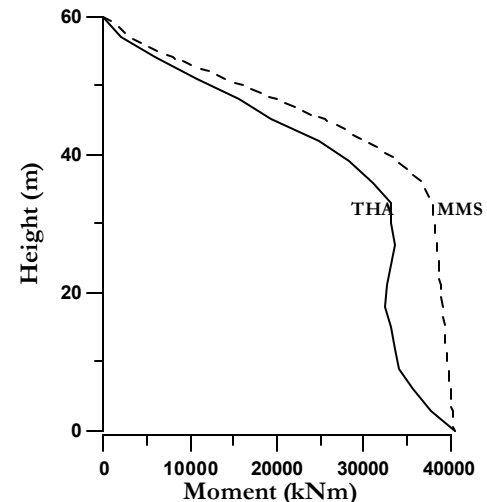
(w) Twenty-Storey Wall, IR=1.5



(p) Twelve-Storey Wall, IR=2.0

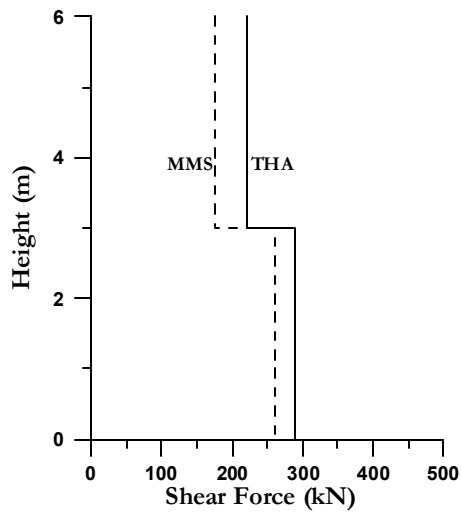


(t) Sixteen-Storey Wall, IR=2.0

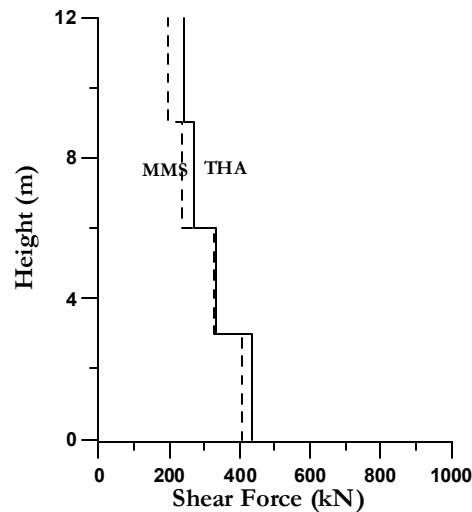


(x) Twenty-Storey Wall, IR=2.0

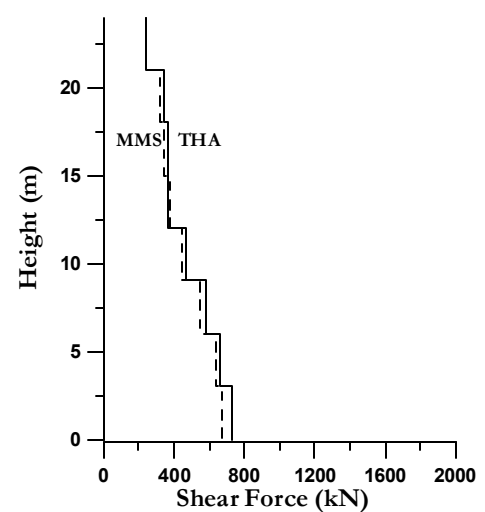
**MMS Moment Envelopes Compared with Time History Results for Different Seismic Intensity Ratios (IR=1=Design)**



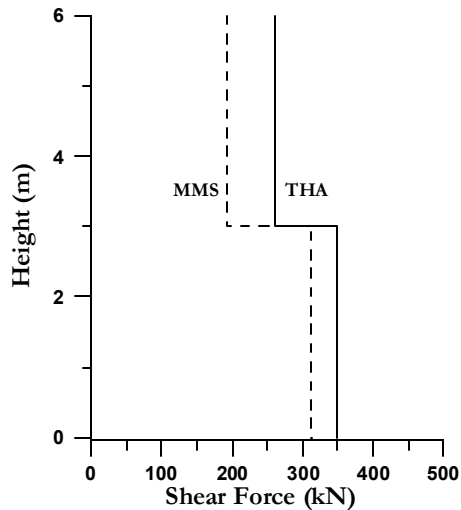
(a) Two-Storey Wall, IR=0.5



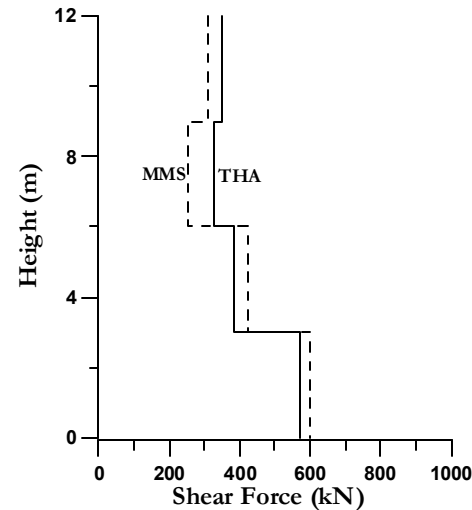
(e) Four-Storey Wall, IR=0.5



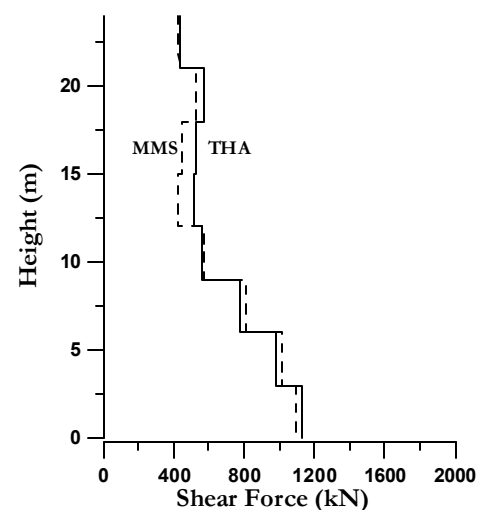
(i) Eight-Storey Wall, IR=0.5



(b) Two-Storey Wall, IR=1.0

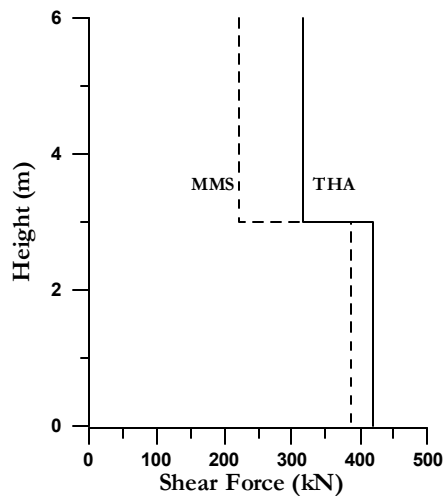


(f) Four-Storey Wall, IR=1.0

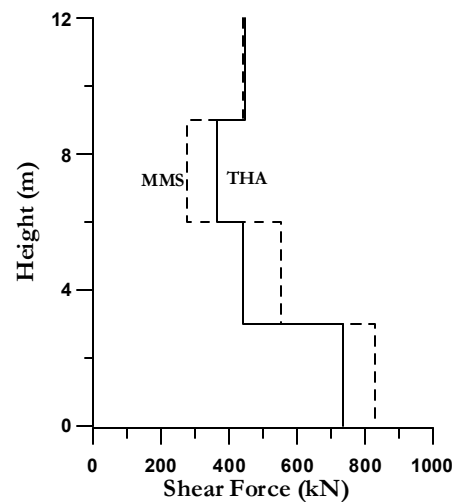


(j) Eight-Storey Wall, IR=1.0

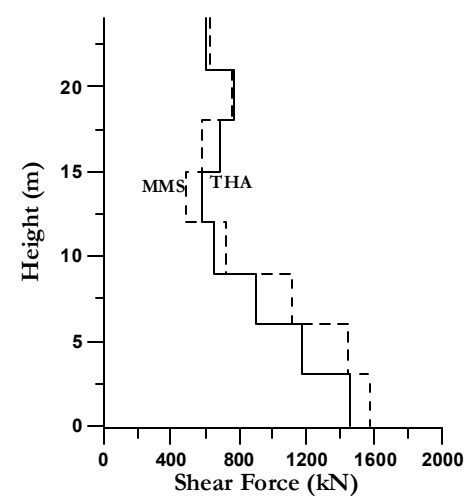
**MMS Shear Profiles Compared with Time History Results for Different Seismic Intensity Ratios (IR=1= Design)**



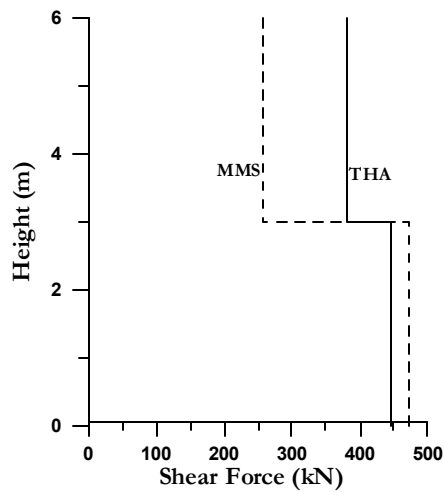
(c) Two-Storey Wall, IR=1.5



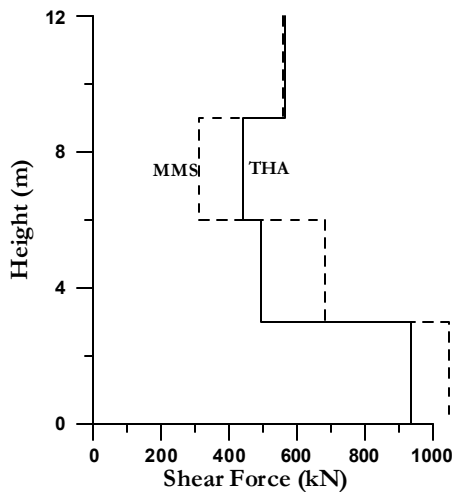
(g) Four-Storey Wall, IR=1.5



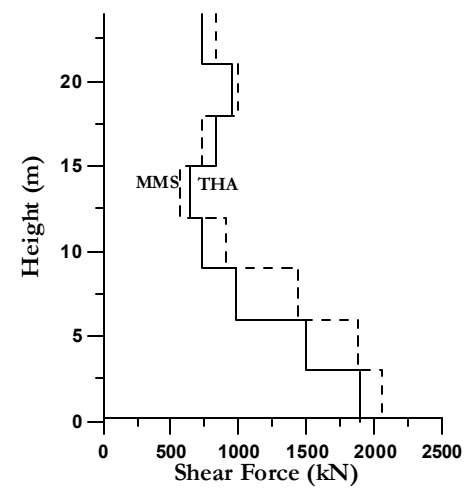
(k) Eight-Storey Wall, IR=1.5



(d) Two-Storey Wall, IR=2.0

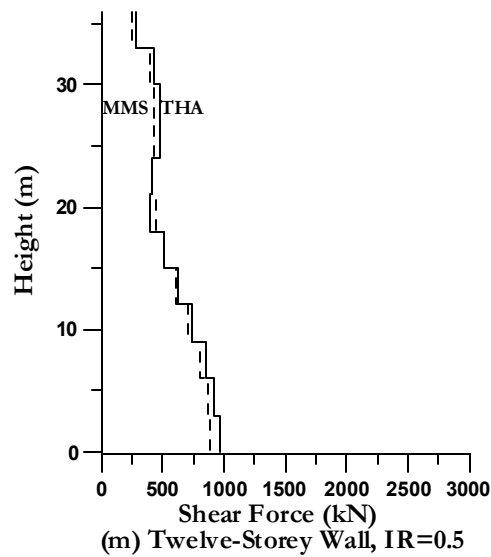


(h) Four-Storey Wall, IR=2.0

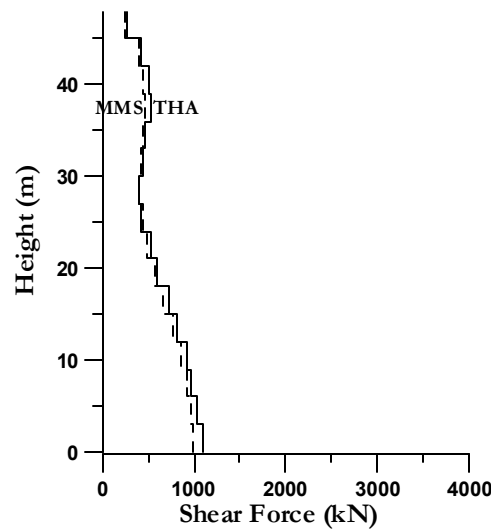


(l) Eight-Storey Wall, IR=2.0

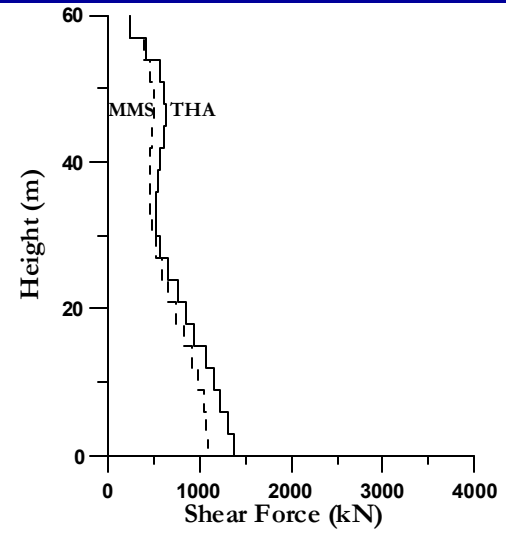
**MMS Shear Envelopes Compared with Time History Results for Different Seismic Intensity Ratios (IR=1= Design)**



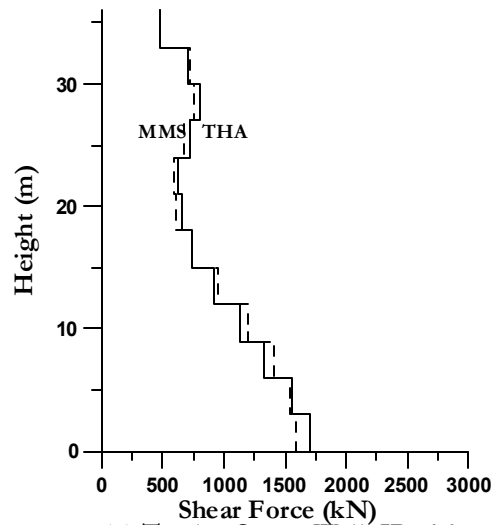
(m) Twelve-Storey Wall, IR=0.5



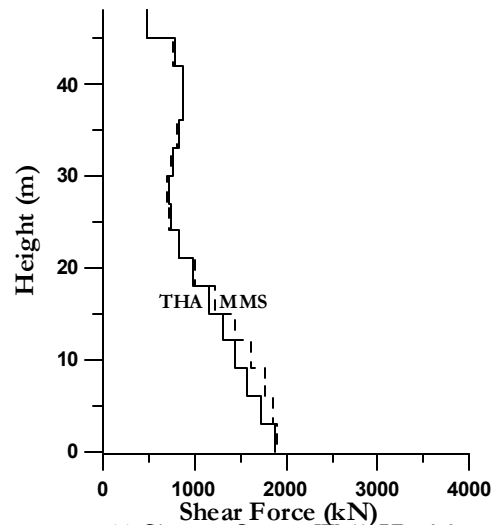
(q) Sixteen-Storey Wall, IR=0.5



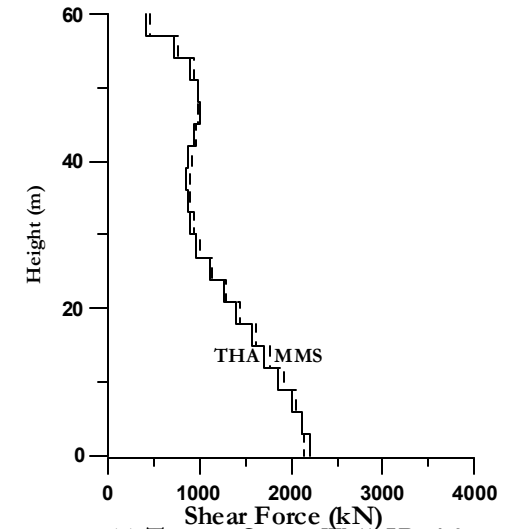
(u) Twenty-Storey Wall, IR=0.5



(n) Twelve-Storey Wall, IR=1.0

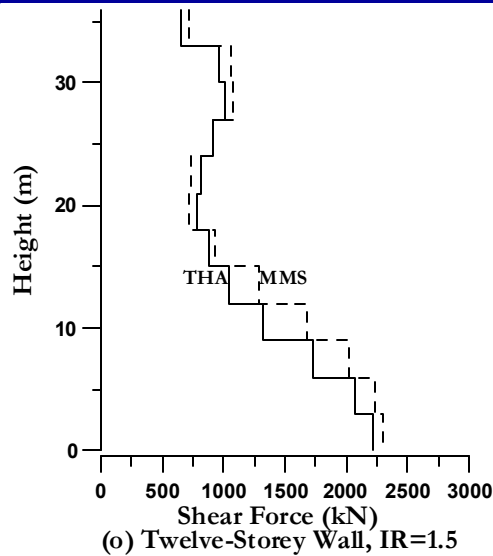


(r) Sixteen-Storey Wall, IR=1.0

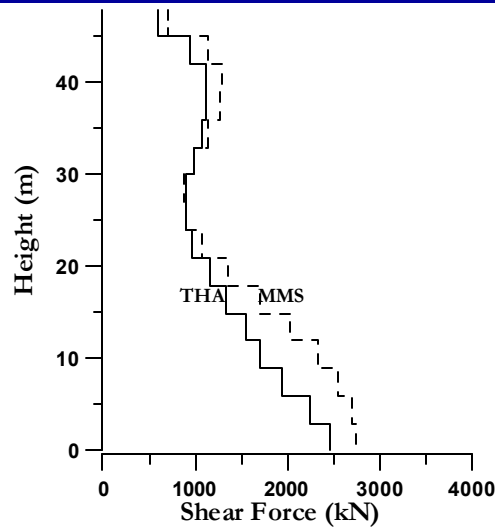


(v) Twenty-Storey Wall, IR=1.0

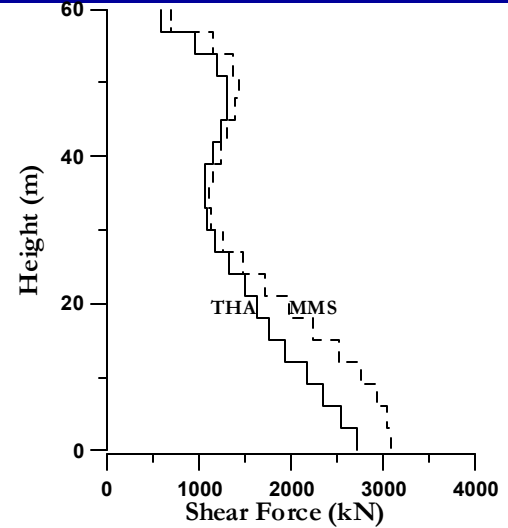
**MMS Shear Envelopes Compared with Time History Results for Different Seismic Intensity Ratios (IR=1= Design)**



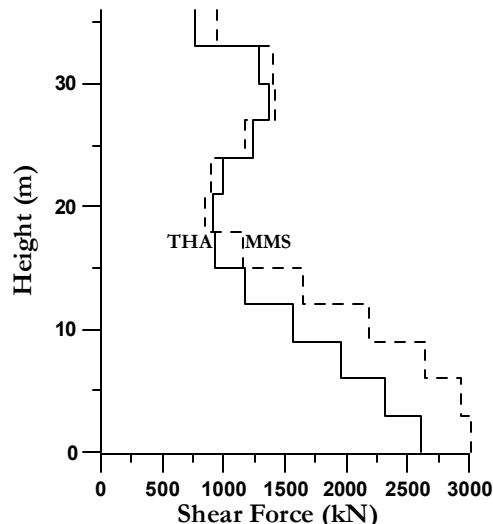
(o) Twelve-Storey Wall, IR=1.5



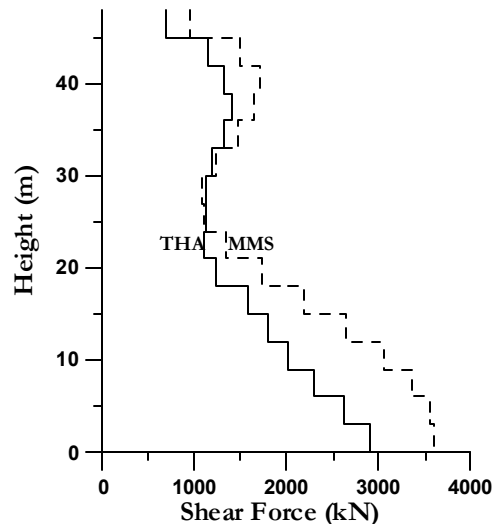
(s) Sixteen-Storey Wall, IR=1.5



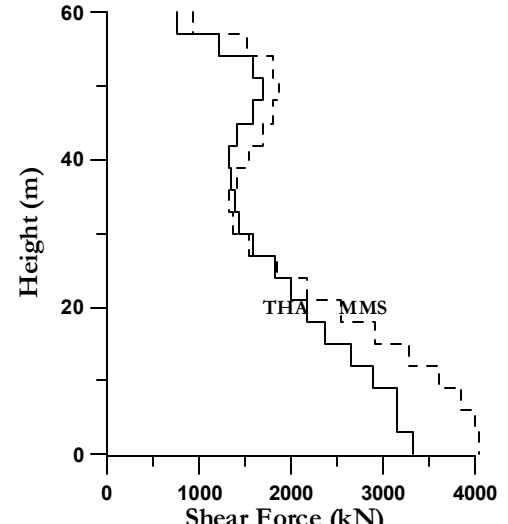
(w) Twenty-Storey Wall, IR=1.5



(p) Twelve-Storey Wall, IR=2.0



(t) Sixteen-Storey Wall, IR=2.0



(x) Twenty-Storey Wall, IR=2.0

**MMS Shear Profiles Compared with Time History Results for Different Seismic Intensity Ratios (IR=1= Design)**

# CONSEQUENCES FOR CAPACITY DESIGN

Results show dynamic amplification increases as intensity ratio (i.e. ductility) increases. Equations can be re-written as

$$V_i = (V_1^2 + m^2 (V_2^2 + V_3^2 + \dots))^{0.5}$$

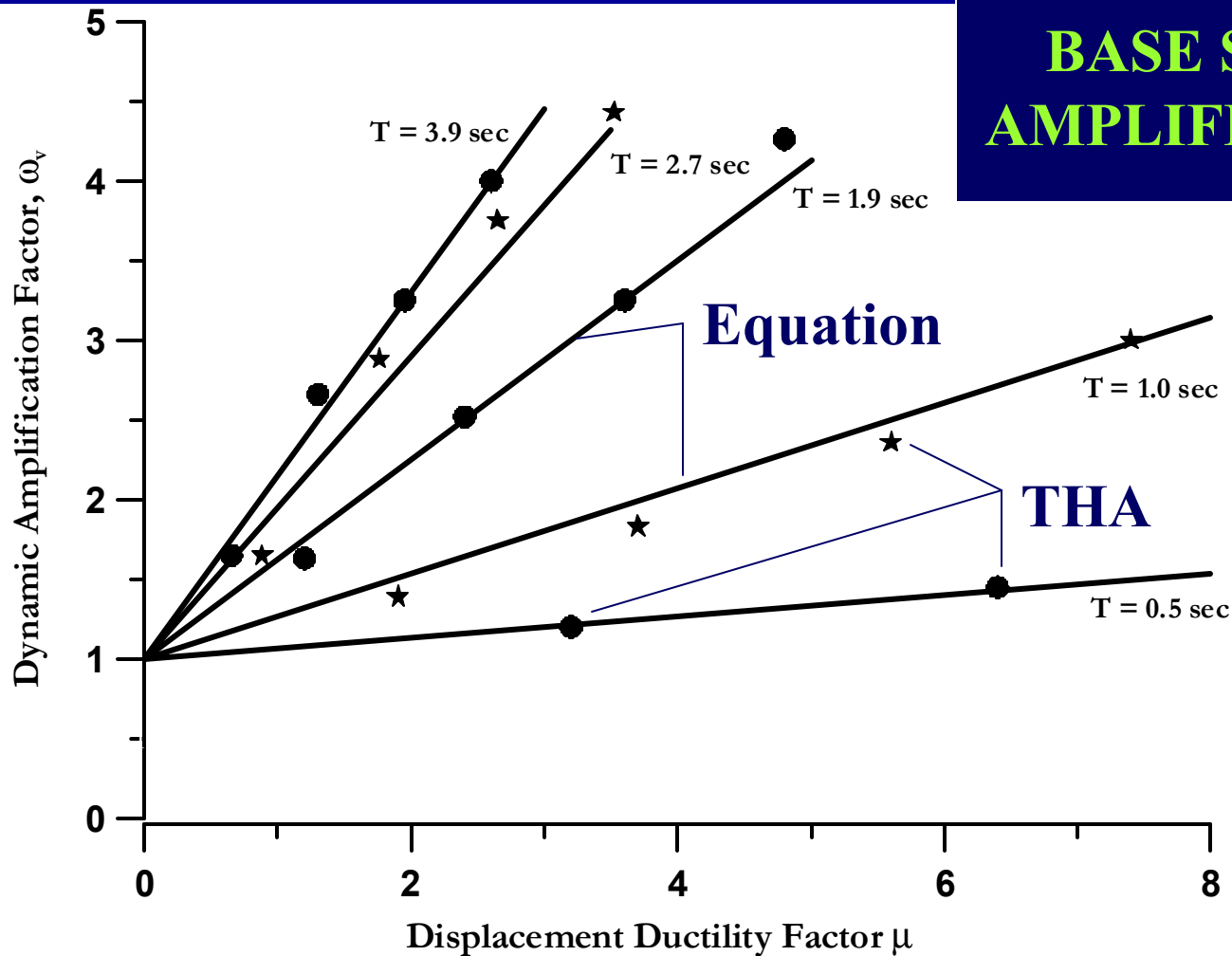
$$M_i = 1.1 * (M_1^2 + m^2 (M_2^2 + M_3^2 + \dots))^{0.5}$$

where  $V_1$   $V_2$   $M_1$   $M_2$  are calculated from the inelastic spectra in accordance with normal design to NZS4203

Dynamic amplification should thus be dependent on Period T (not number of storeys), and ductility m.

**Note:** Relationship should be linear with m

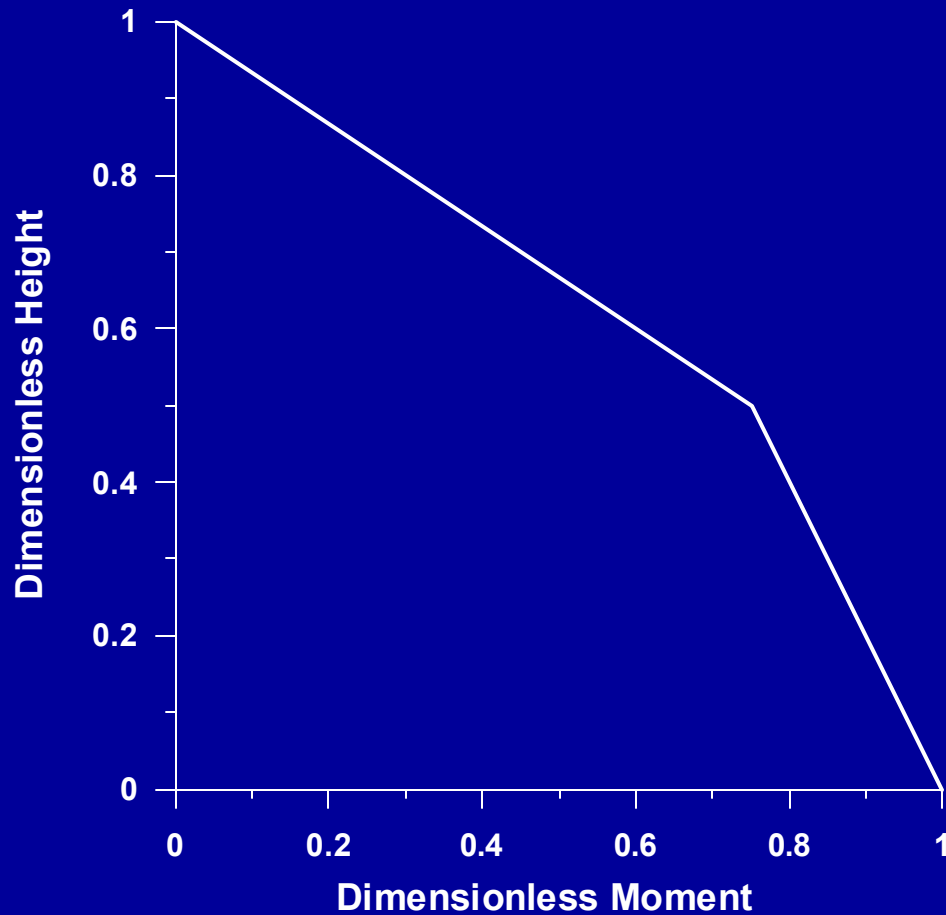
# BASE SHEAR AMPLIFICATION



$$w_v = 1 + m \cdot B_{(T)} \quad \text{where} \quad 0.067 \leq B_{(T)} = 0.067 + 0.4(T - 0.5) \leq 1.15$$

With flexural overstrength  $f^o$ :

$$V_R = f^o w_v V_E \quad \text{where} \quad w_v = 1 + \frac{m}{f^o} B_{(T)}$$



## Suggested Design Moment Profile

**Bilinear, with moment  
at midheight = 0.75 x  
Base Moment**

# CONCLUSIONS

- **Current Dynamic Amplification for Moments and Shears in Cantilever Walls is inadequate.**
- **Dynamic Amplification Depends on Period and Ductility**
- **Two methods (MMS and simple equation) were Developed to Estimate Dynamic Amplification**
- **Design to the  $Z = 1.2$  regions in NZ is Equivalent to a PGA of 0.27g in European Design**
- **Design to Maximum Permitted Ductility in NZS 4203 will Result in Drift Levels that Exceed 0.02 for all but very low Buildings**