MOTEMS Structural Damping

Prevention First 2018 Conference

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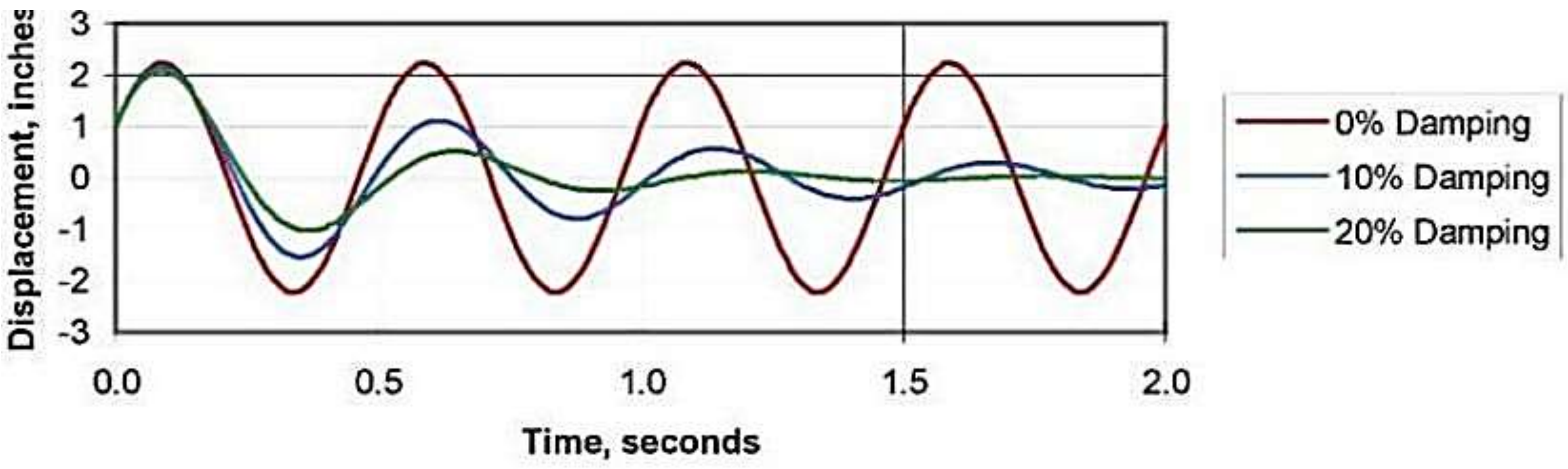
Outline

- What is Damping?
- Current Codes/Standards Damping Equations
- Case Study
- Analysis Results
- Conclusion

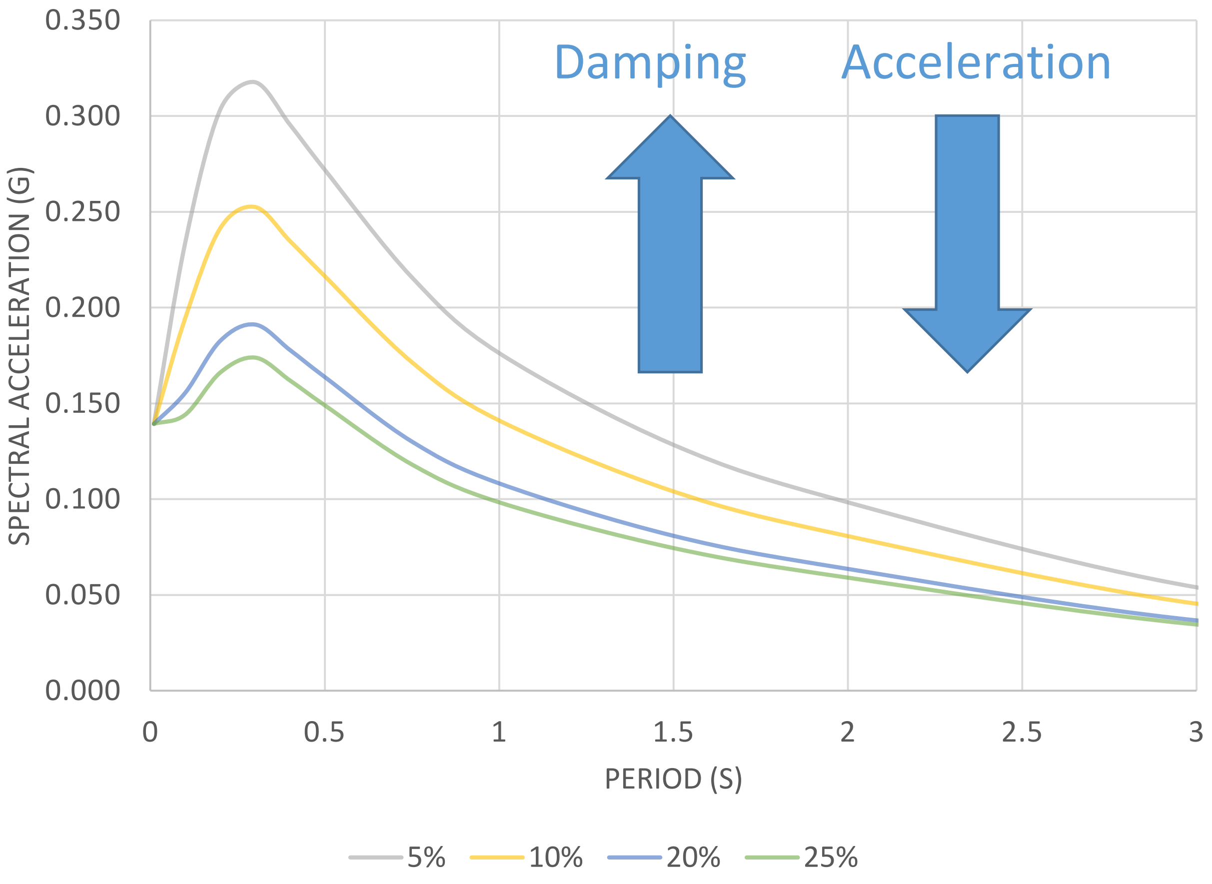
What is Damping?

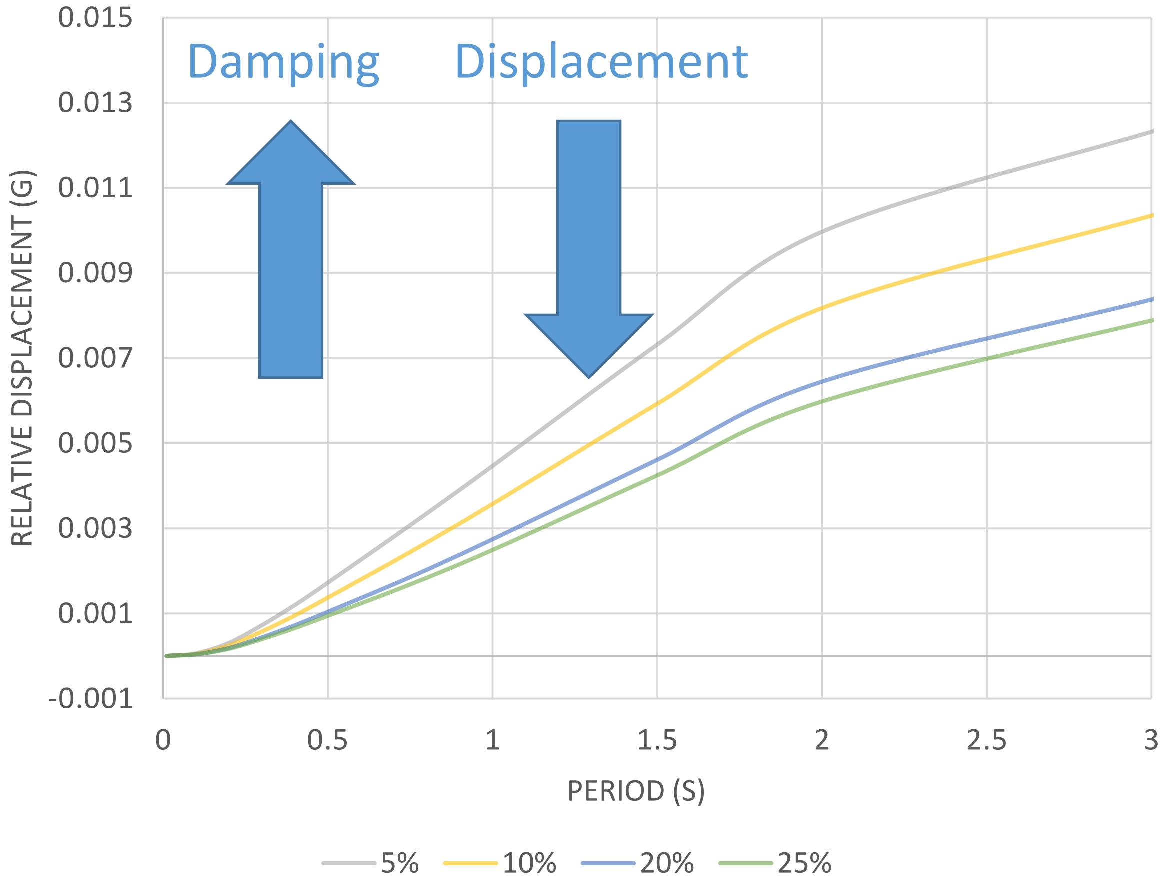
What is Damping?

- Damping is the phenomenon that makes any vibrating structure decay in amplitude of motion gradually by means of energy dissipation
- Damping = Energy dissipation
- Higher damping = Lower displacement



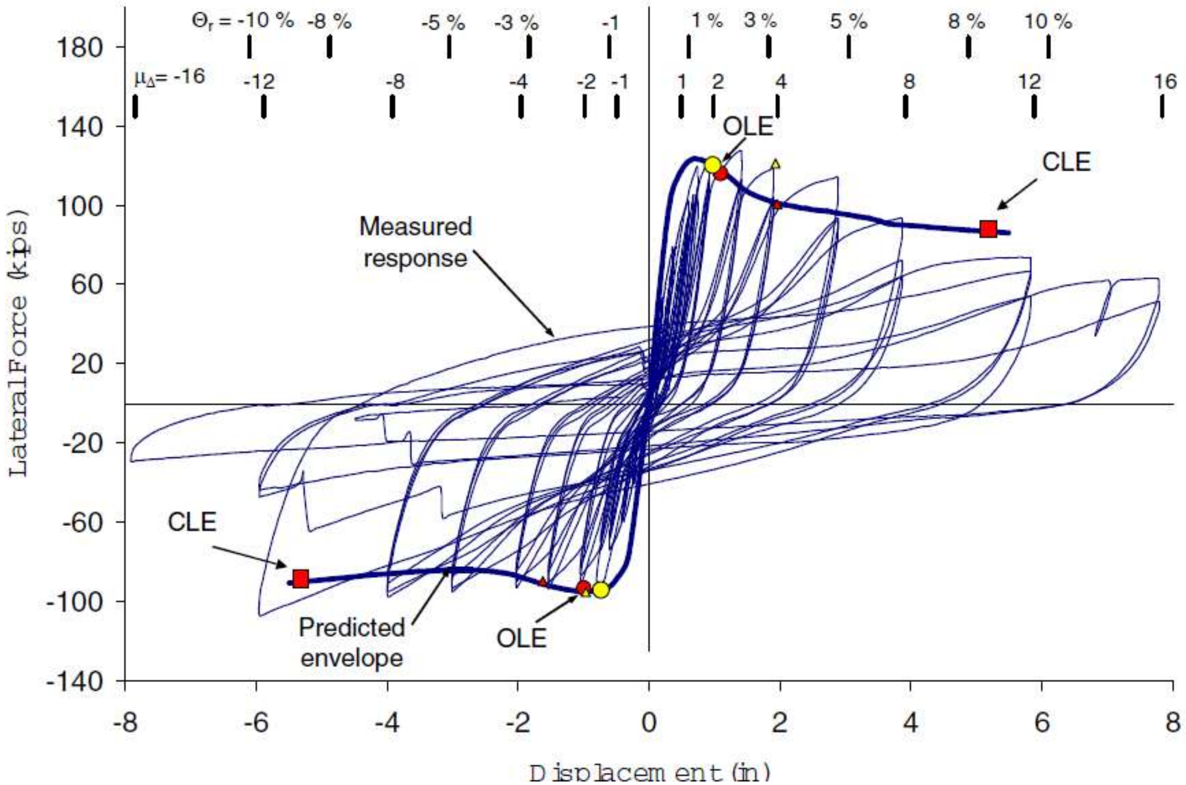
Spectral Acceleration and Displacement





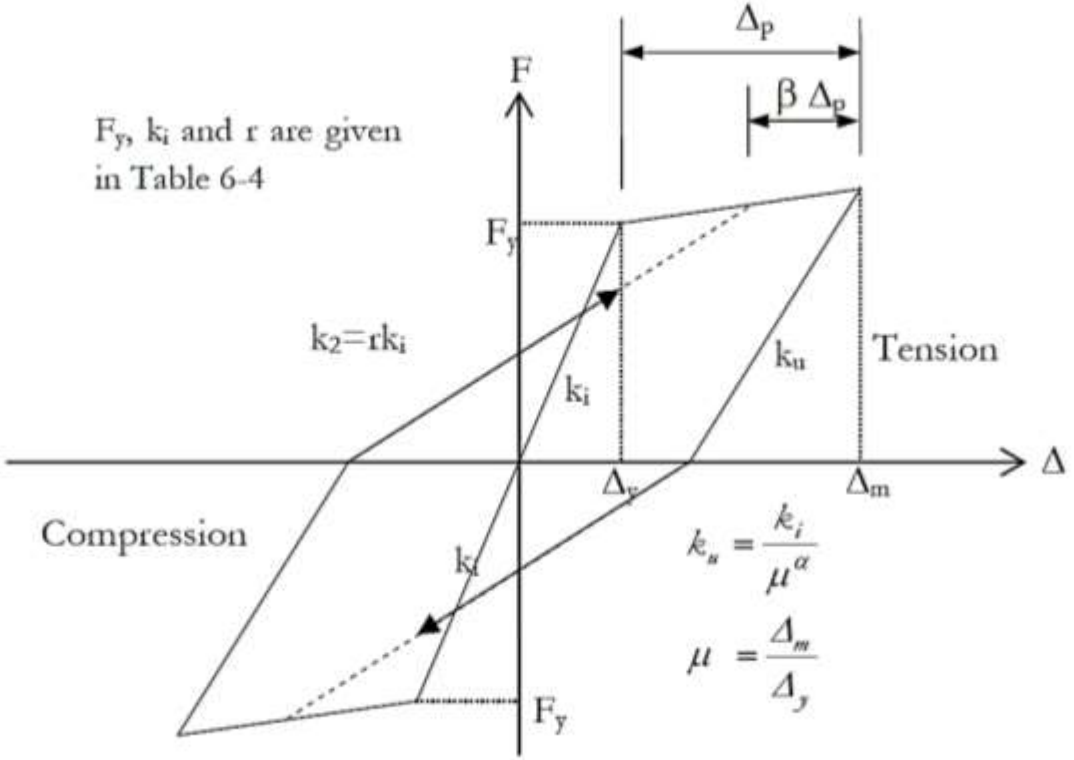
Damping Types

- Coulomb damping: sliding
- Radiation damping: soil structure interaction
- Hysteric damping: internal material deformations
- System damping

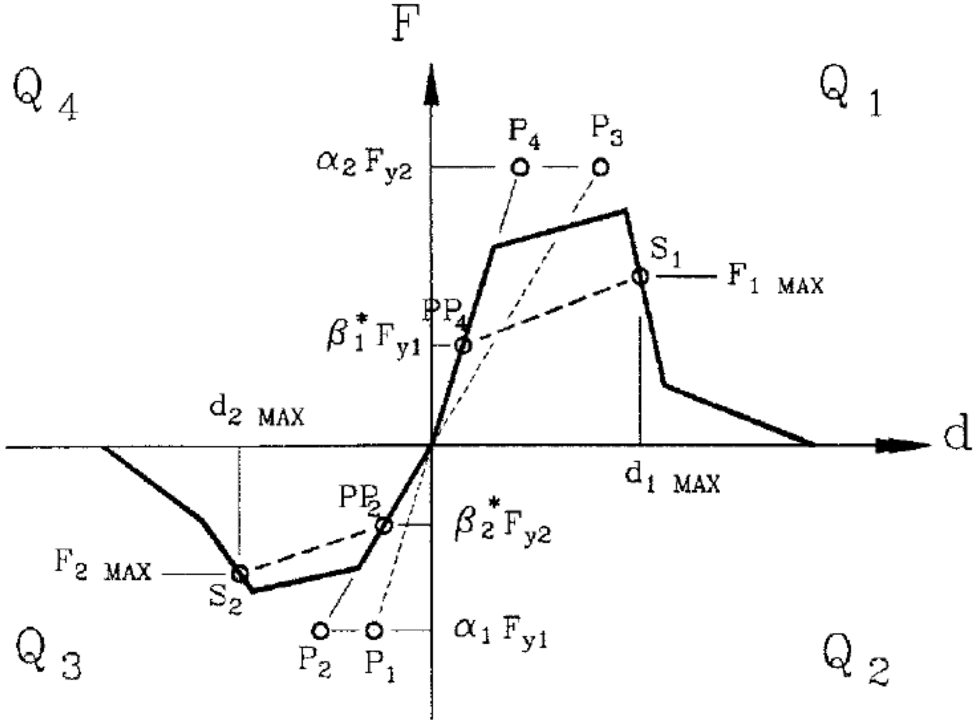


Hysteretic Modeling for Nonlinear Analysis

Takeda Model



Pivot Model



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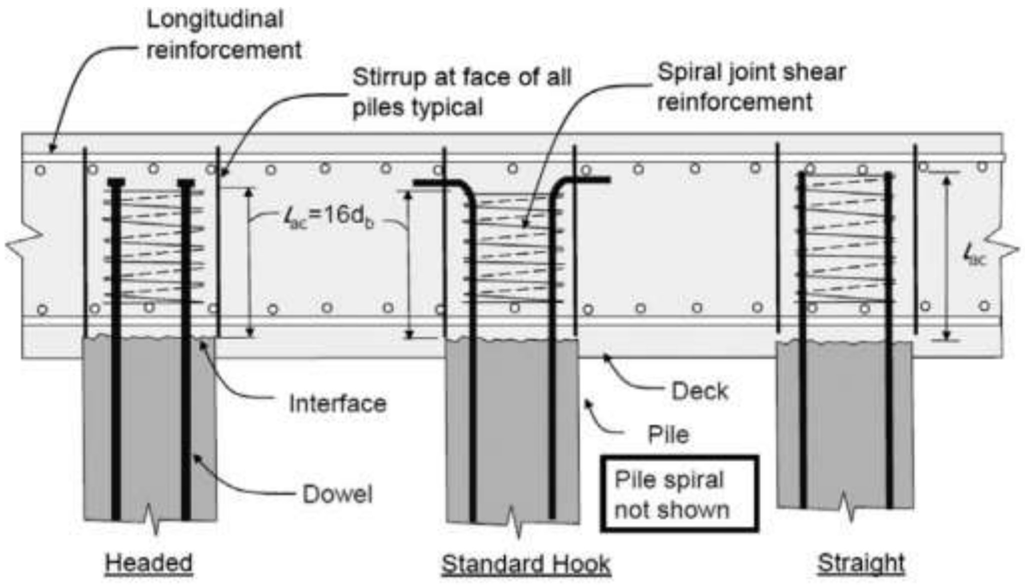
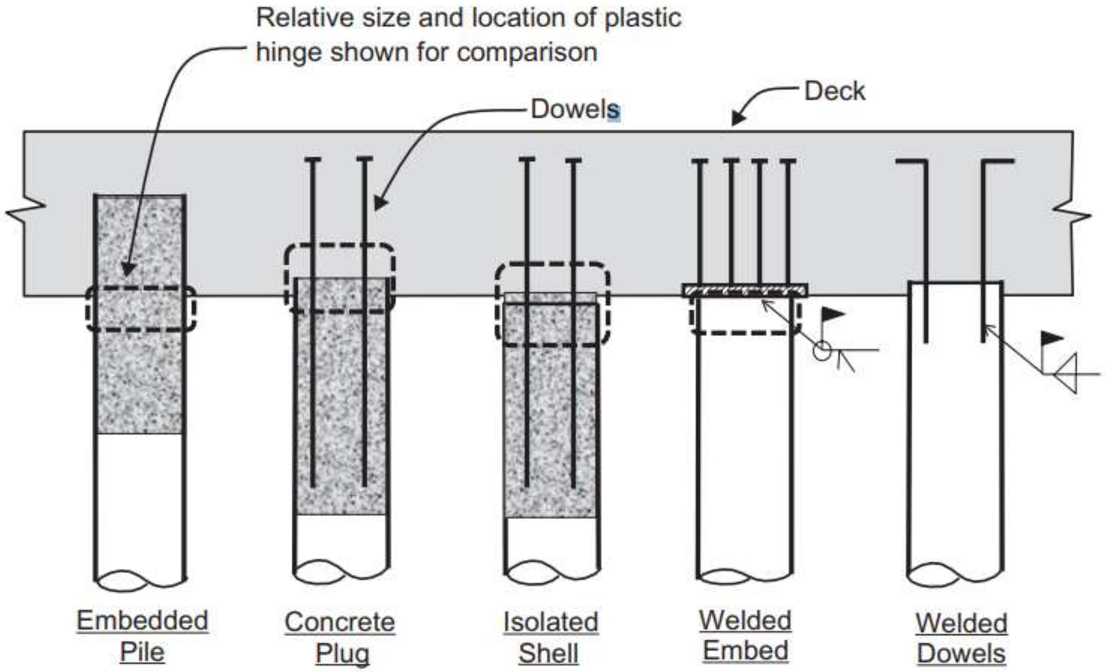
Elements that Affect Damping

- Material type: timber, concrete, steel
- Structure-soil interaction
- Ductility demand level
  - Higher ductility structures will have higher damping
- Connection Type
  - Concrete pile-to-deck connection
  - Steel pile-to-deck connection, allowed only using concrete plug
  - Timber pile-to-deck connection

ASCE 61-14 - Connections

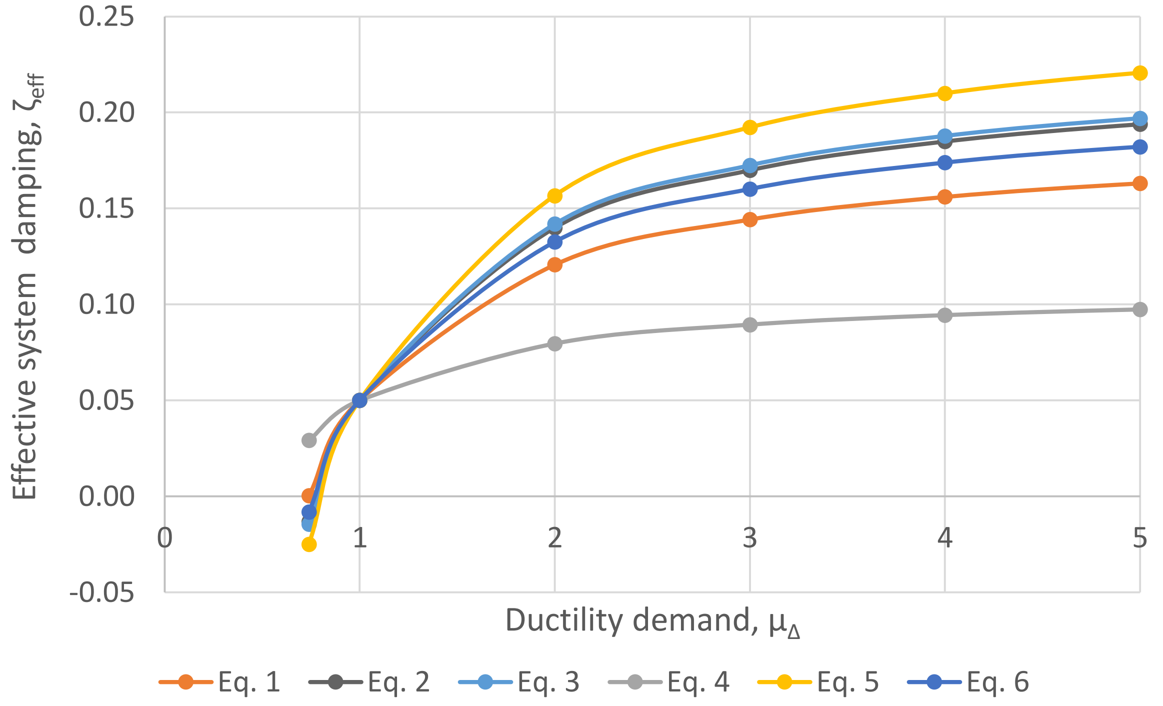




Effective Damping for Different Structure Type and Material

- *"Displacement Based Seismic Design of Structures" by Priestley, Calvi, and Kowalsky*

Structure	Equation
Concrete Wall Building, Bridges	Eq1: $\xi_{eff} = 0.05 + 0.444\left(\frac{\mu_\Delta - 1}{\mu_\Delta * \pi}\right)$
Concrete Frame Building	Eq2: $\xi_{eff} = 0.05 + 0.565\left(\frac{\mu_\Delta - 1}{\mu_\Delta * \pi}\right)$
Steel Frame Building	Eq3: $\xi_{eff} = 0.05 + 0.577\left(\frac{\mu_\Delta - 1}{\mu_\Delta * \pi}\right)$
Hybrid Prestressed Frame	Eq4: $\xi_{eff} = 0.05 + 0.186\left(\frac{\mu_\Delta - 1}{\mu_\Delta * \pi}\right)$
Friction Slider	Eq5: $\xi_{eff} = 0.05 + 0.670\left(\frac{\mu_\Delta - 1}{\mu_\Delta * \pi}\right)$
Bilinear Isolation Systems	Eq6: $\xi_{eff} = 0.05 + 0.519\left(\frac{\mu_\Delta - 1}{\mu_\Delta * \pi}\right)$



Timber Damping

- Not defined in MOTEMS
- Comes from yielding of connections
- Limited research
- 10% to 15% damping

TABLE 3. RECOMMENDED DAMPING VALUES

Stress Level	Type and Condition of Structure	Percentage Critical Damping
Working stress, no more than about ½ yield point	• Vital piping	1 to 2
	• Welded steel, prestressed concrete, well reinforced concrete (only slight cracking)	2 to 3
	• Reinforced concrete with considerable cracking	3 to 5
	• Bolted and / or riveted steel, wood structures with nailed or bolted joints	5 to 7
At or just below yield point	• Vital piping	2 to 3
	• Welded steel, prestressed concrete (without complete loss in prestress)	5 to 7
	• Prestressed concrete with no prestress left	7 to 10
	• Reinforced concrete	7 to 10
	• Bolted and / or riveted steel, wood structures, with bolted joints	10 to 15
	• Wood structures with nailed joints	15 to 20

Newmark, Hall Earthquake Spectra EERI 1982

Timber Hysteretic Damping

- Possible to get ductile response from bolted connections
- Damping can be calculated from Hysteretic loop
- Recommend 10% for design

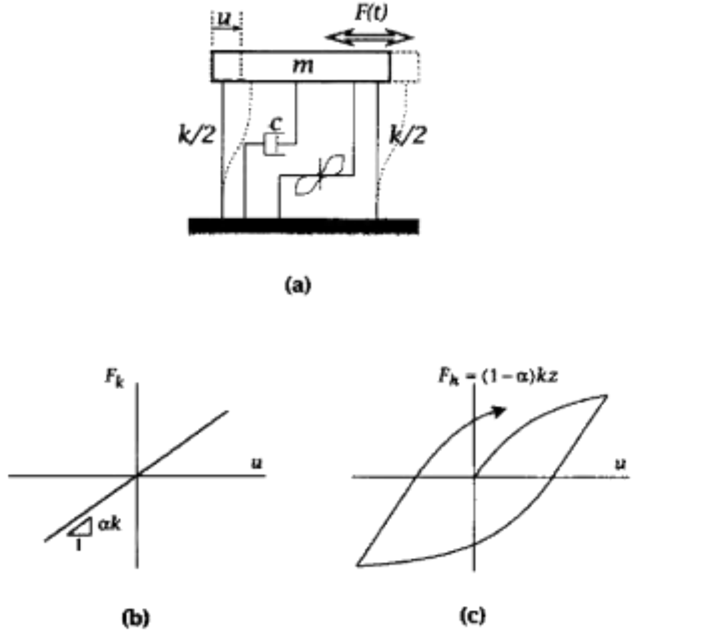


FIG. 3. Hysteretic SDOF System: (a) Schematic Model; (b) Non-damping Linear Restoring-Force Component; (c) Hysteretic Restoring-Force Component

Foliente, G.C., *Hysteresis Modeling of Wood Joints and Structural Systems*, Journal of Structural Engineering, June 1995, Page 1013-1022.

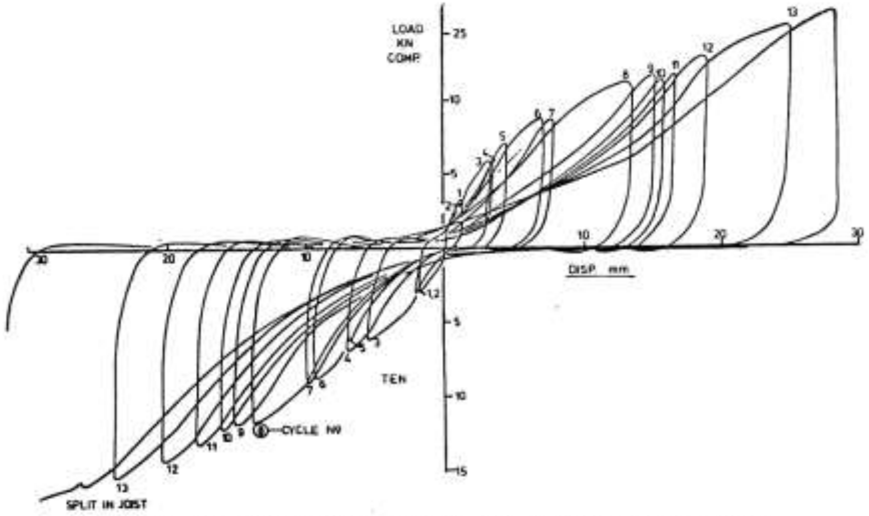


Fig 7. HYSTERESIS LOOPS FOR BOLTED TIMBER STRUT CONNECTION UNDER PUSH-PULL LOADING (REF.D1).

Hysteretic Loop for Bolted Strut Connection

[Wood, J.H., Cooney, R.C., and Potter, S.M., *Cyclic Testing of Connections for Light Timber Construction*, NZMWD Central Labs, Report No 5-76/12 (Bolts, Pryde Nail Plates, etc.), 1976.]

Current Codes/Standards Damping Equations

Published Effective System Damping Equations

1. Proposed MOTEMS-2019

$$\xi_{eff} = 0.05 + \frac{1}{\pi}\left(1 - \frac{1-\alpha_1}{\sqrt{\mu_\Delta}} - \alpha_1\sqrt{\mu_\Delta}\right)$$

2. MOTEMS-2016/ ASCE 61-14/ UFC 4-152-01-2017

$$\xi_{eff} = 0.05 + \frac{1}{\pi}\left(1 - \frac{1-r}{\sqrt{\mu_\Delta}} - r\sqrt{\mu_\Delta}\right)$$

3. ACI-SP-295-3-2013 /POLA Seismic Code 2010/ POLB WDC 4.0-2015

$$\xi_{eff} = 0.10 + 0.565\left(\frac{\mu_\Delta - 1}{\mu_\Delta * \pi}\right)$$

4. "Displacement Based Seismic Design of Structures" by Priestley, Calvi, and Kowalsky, 2007

$$\xi_{eff} = 0.05 + 0.565\left(\frac{\mu_\Delta - 1}{\mu_\Delta * \pi}\right)$$

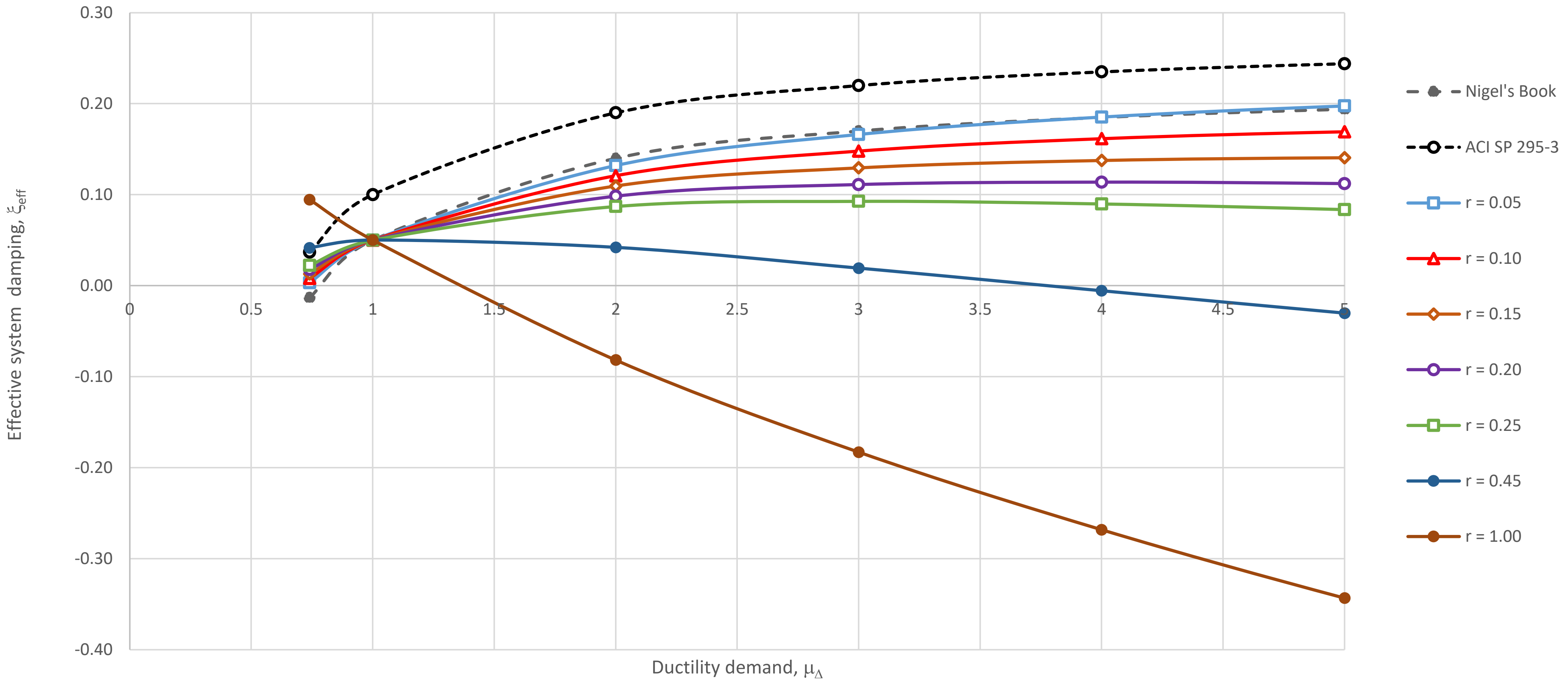
Effective Damping Equations Comparison

- Effective damping, ξ_{eff}, is function of displacement ductility, μ_Δ
- First term in all equations includes damping value of 0.05 or 0.10
  - These values are not stated to be the minimum values of ξ_{eff}
- Second equation's term is negative when μ_Δ < 1.0
- The ratio of second slope over elastic slope for the idealized bi-linear pushover curve, r, could be negative value but should be ≤ 1.00

Effective Damping Equations Comparison Summary

Damping Equation	First Term	Second Term is Negative	Effective Damping, ξ_{eff} is Negative	
			μ_Δ	r
MOTEMS	0.05	$\mu_\Delta < 1$	< 0.74 < 1.38	-0.05 1.00
ACI SP 295-3	0.10	$\mu_\Delta < 1$	< 0.63	NA
Priestley, et al	0.05	$\mu_\Delta < 1$	< 0.76	NA

Effective System Damping vs Ductility Demand



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Case Study

Case Study Scope - Δ_y

- Effective damping, ξ_{eff}, is function of displacement ductility, μ_Δ, and therefore a function of the yield displacement, Δ_y
- The yield displacement, Δ_y, is determined based on pushover curve bi-linearization using equal area method, therefore:
  - MOTEMS – Δ_y is not necessarily the same for Level 1 and Level 2 earthquakes based on pushover curve bi-linearization at Level 1 and Level 2 displacement demand
  - POLA/ POLB - Δ_y is the same for Level 1 and Level 2 earthquakes based on pushover curve bi-linearization at Level 2 displacement demand
  - Proposed Approach - Δ_y is the same for Level 1 and Level 2 earthquakes based on pushover curve bi-linearization at ultimate displacement capacity using references below:
    - Gulkan and Sozen, Inelastic Response of Reinforced Concrete Structures to Earthquake Motions, ACI Journal, Dec 1974
    - Shibata and Sozen, Substitutes structures Method for Seismic Design in Reinforced Concrete, ASCE Structural Journal, Vol 102 NO ST1 Jan 1976
    - ASCE 61-14 Commentary Section C6.8.3

Case Study Scope – “r”

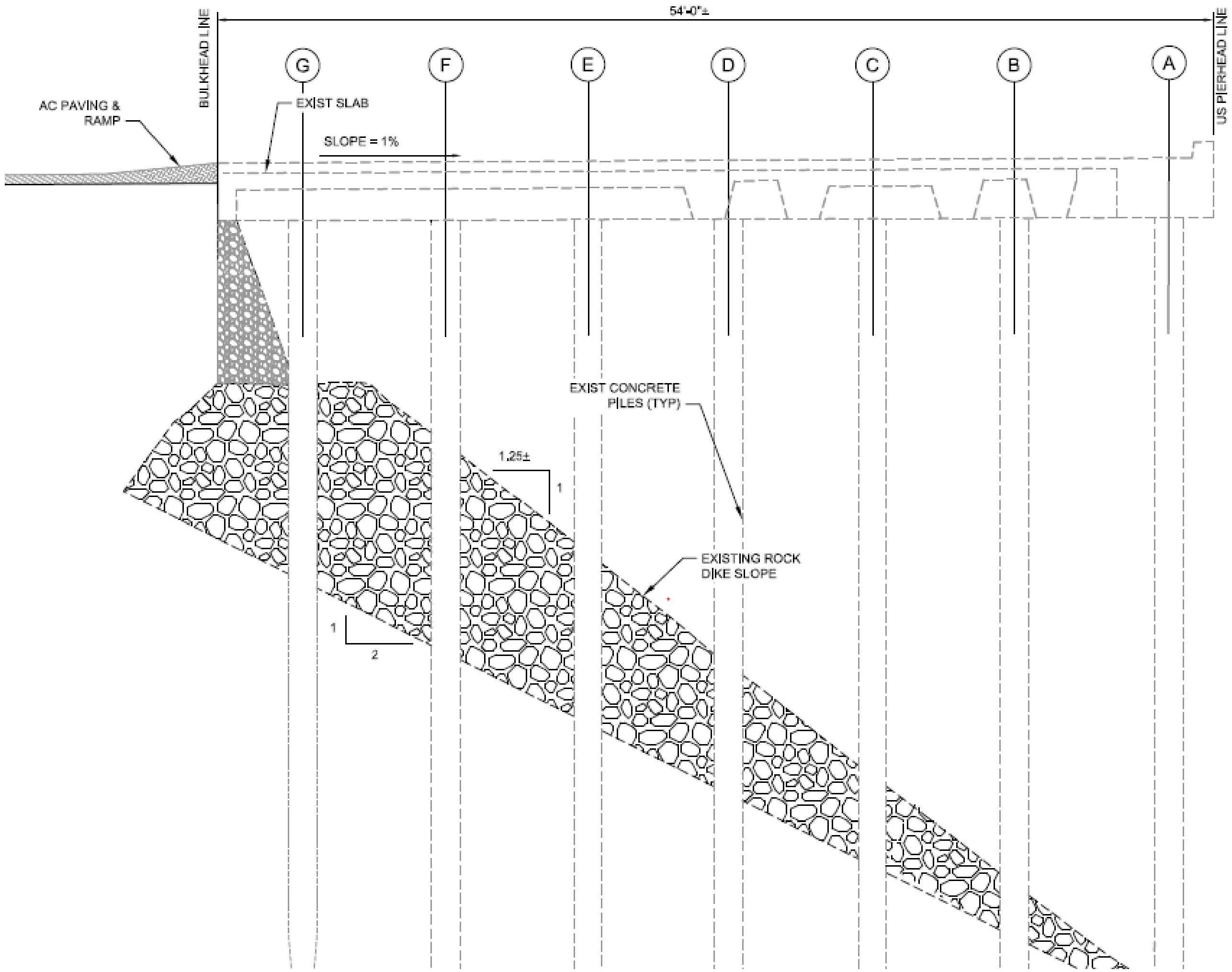
- For MOTEMS, effective damping, ξ_{eff}, is function of “r”
  - The pushover curve bi-linearization results in different ratios of the second slope over elastic slope, “r”
  - “r” value changes for Level 1 and Level 2 earthquakes
- POLA/ POLB – ξ_{eff} is not a function of “r”
- Proposed Approach - ξ_{eff} is not a function of “r”

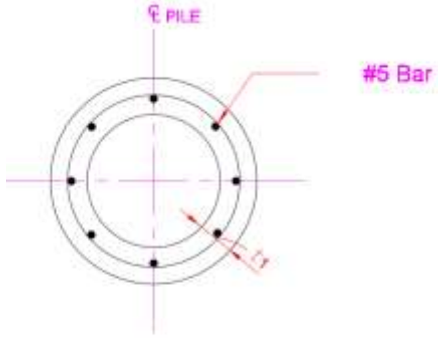
Analysis Cases

- Case 1 - 18” Hollow concrete pipe pile
  - Two soil conditions: Lower bound (LB) with 0.3 multiplier and upper bound (UB) with 2.0 multiplier
  - Level 1 and Level 2 earthquakes

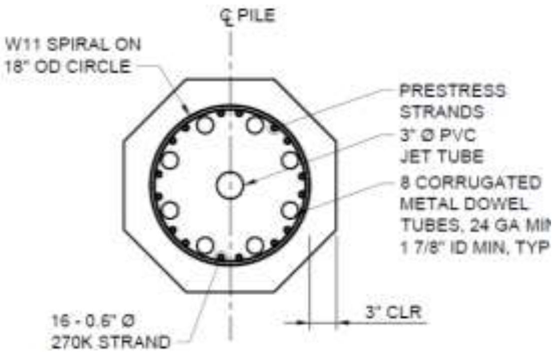
- Case 2- 24” Prestressed concrete pile
  - Two soil conditions: Lower bound (LB) with 0.3 multiplier and upper bound (UB) with 2.0 multiplier
  - Level 1 and Level 2 earthquakes

Wharf Cross-section

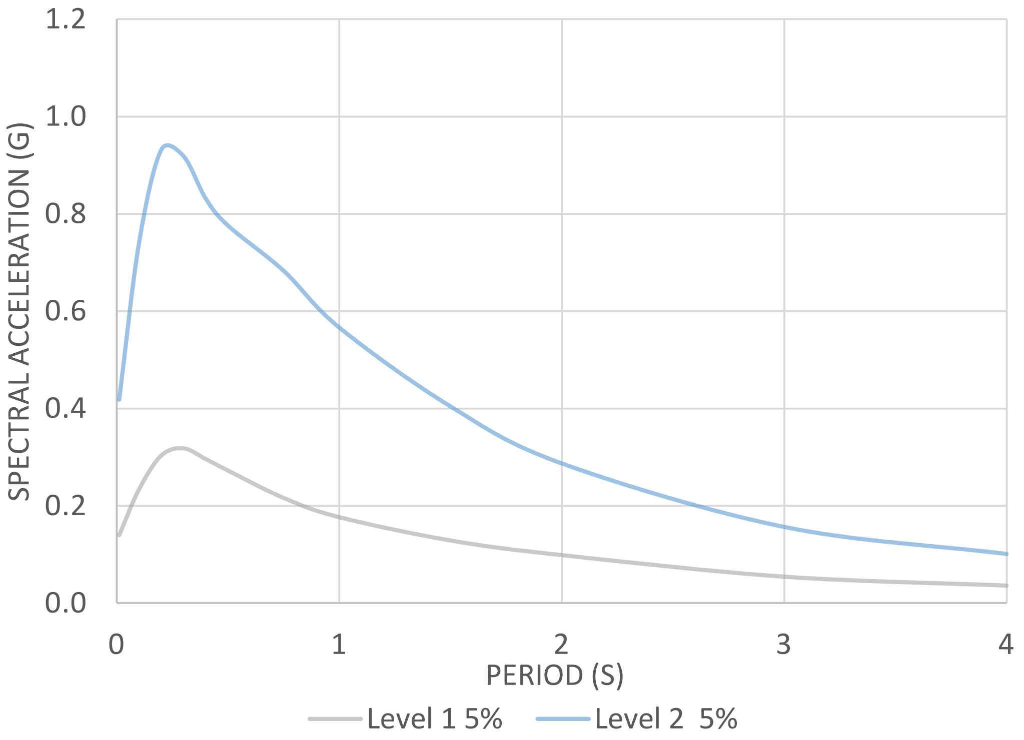


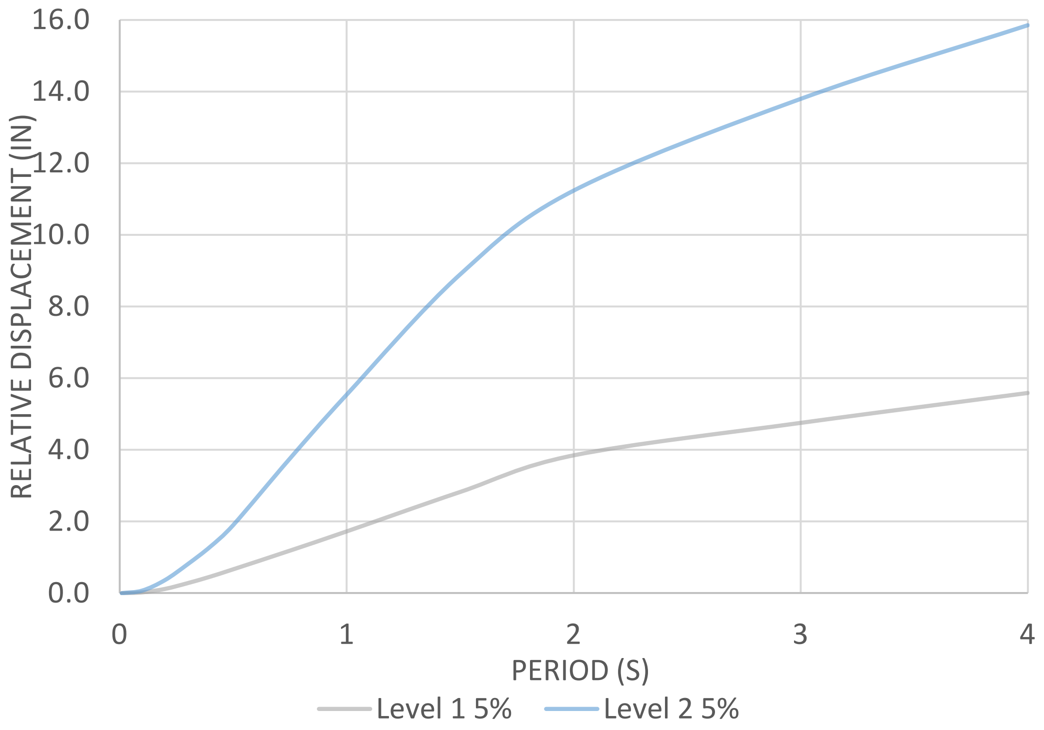


18" Hollow concrete pipe pile



24" Prestressed concrete pile


1.2
1.0
0.8
0.6
0.4
0.2
0.0
SPECTRAL ACCELERATION (G)
0
1
2
3
4
PERIOD (S)
Level 1 5%
Level 2 5%


16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
RELATIVE DISPLACEMENT (IN)
0
1
2
3
4
PERIOD (S)
Level 1 5%
Level 2 5%

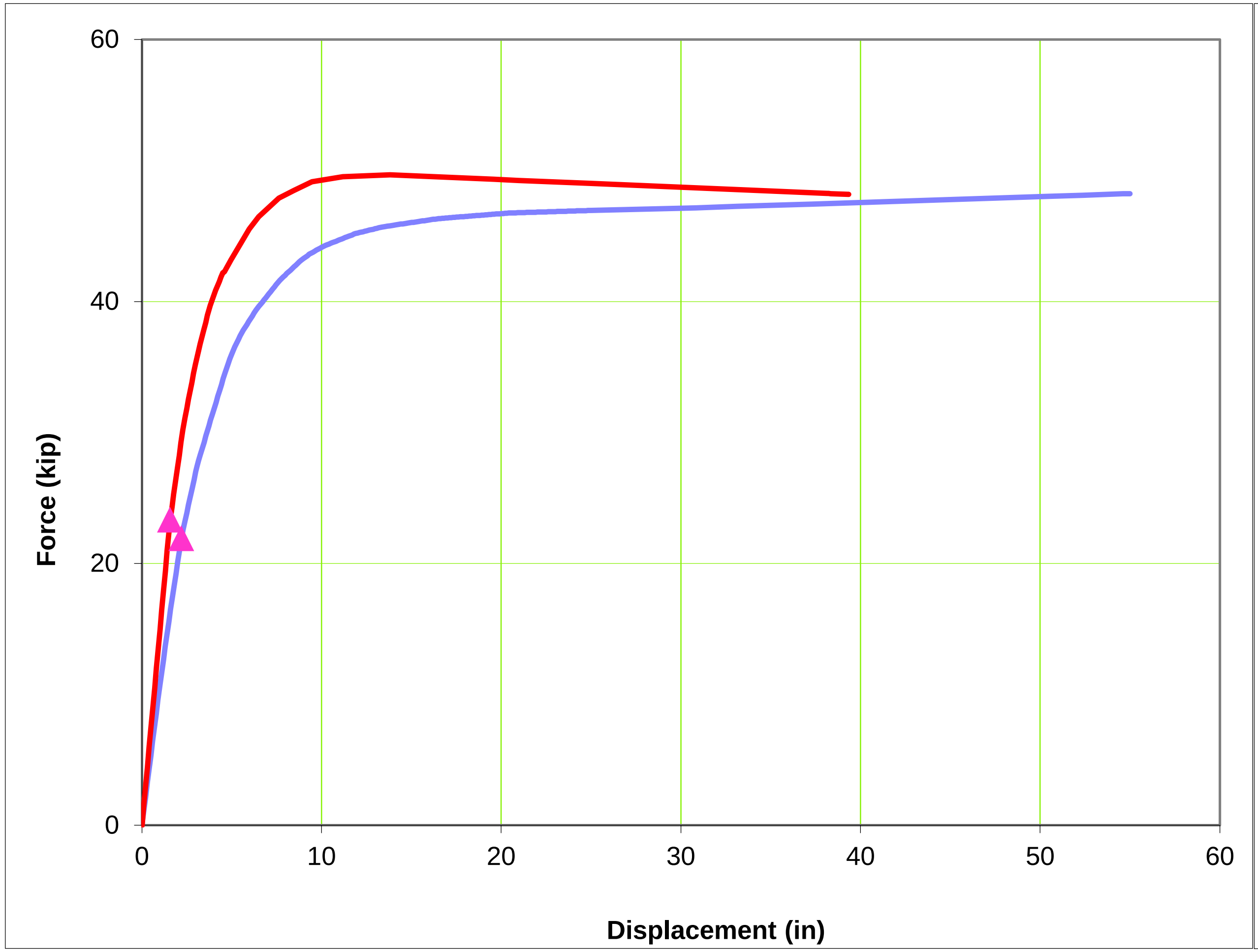
Analysis Approach

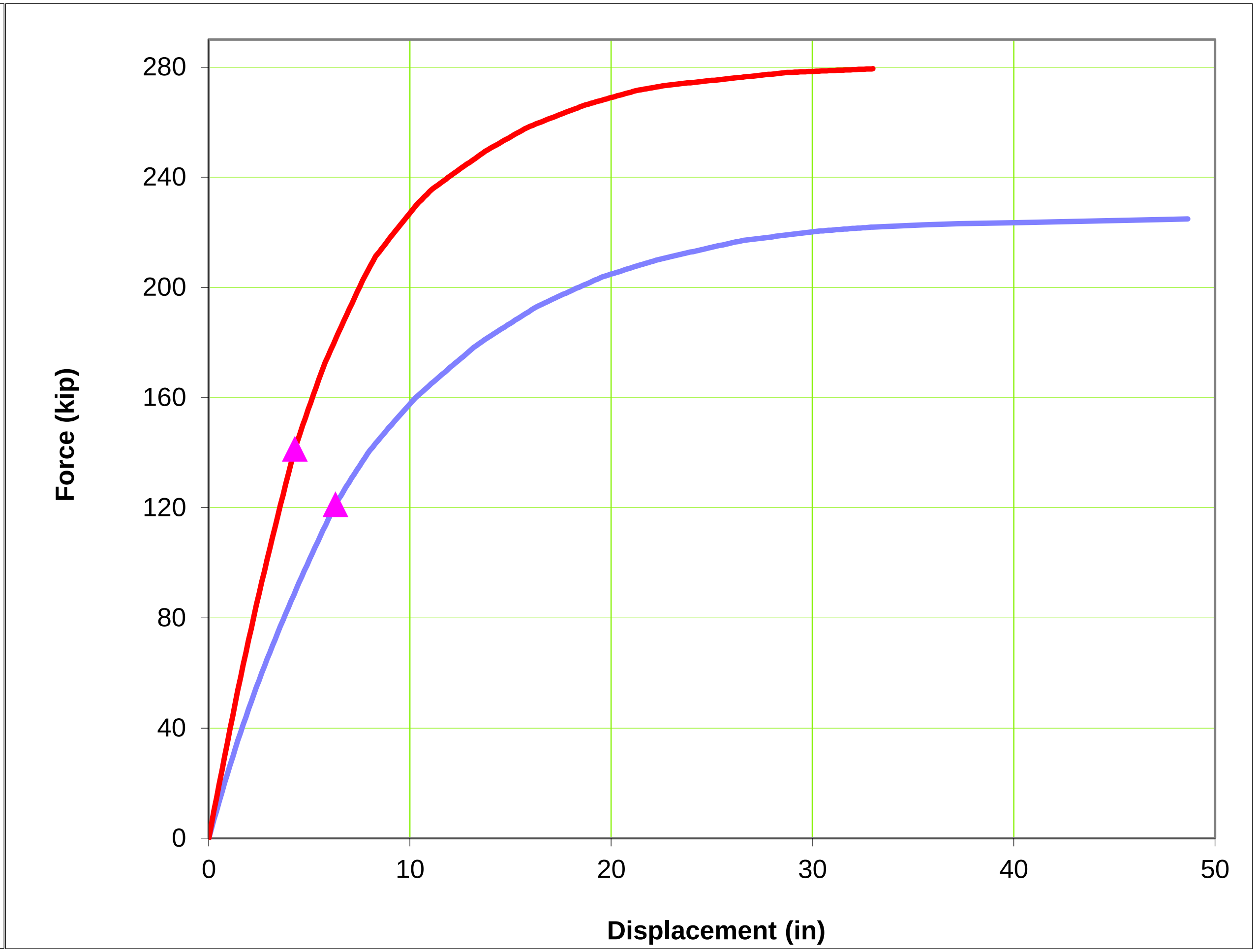
- Substitutes Structures Method (SSM) was used to determine displacement demand
  - MOTEMS pushover curve bi-linearization and effective damping equation with "r"
  - POLA/POLB pushover curve bi-linearization and effective damping equation without "r"
  - Proposed Approach – proposed pushover curve bi-linearization and effective damping equation without "r"
  - Effective damping was determined by applying the minimum damping of 5% for MOTEMS damping equation and 10% for POLA/POLB damping equation
- Two connections
- Two earthquakes
- Two soil conditions

Analysis Cases Summary

Analysis Approach	Case 1 - 18" Hollow Concrete Pipe Pile				Case 2 - 24" Octagonal Concrete Pile			
	LB - L1	LB - L2	UB - L1	UB - L2	LB - L1	LB - L2	UB - L1	UB - L2
A: MOTEMS	C1LBL1-A	C1LBL2-A	C1UBL1-A	C1UBL2-A	C2LBL1-A	C2LBL2-A	C2UBL1-A	C2UBL2-A
B: POLA/POLB	C1LBL1-B	C1LBL2-B	C1UBL1-B	C1UBL2-B	C2LBL1-B	C2LBL2-B	C2UBL1-B	C2UBL2-B
C: Proposed Approach	C1LBL1-C	C1LBL2-C	C1UBL1-C	C1UBL2-C	C2LBL1-C	C2LBL2-C	C2UBL1-C	C2UBL2-C

Analysis Results





Pushover Curve - Case 1 LB & UB

Pushover Curve - Case 2 LB & UB

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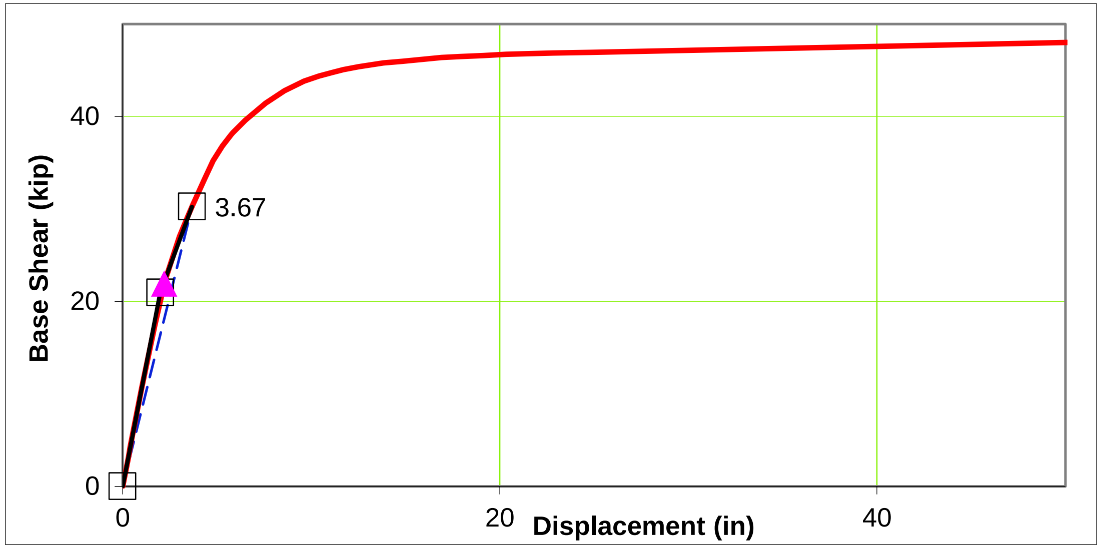
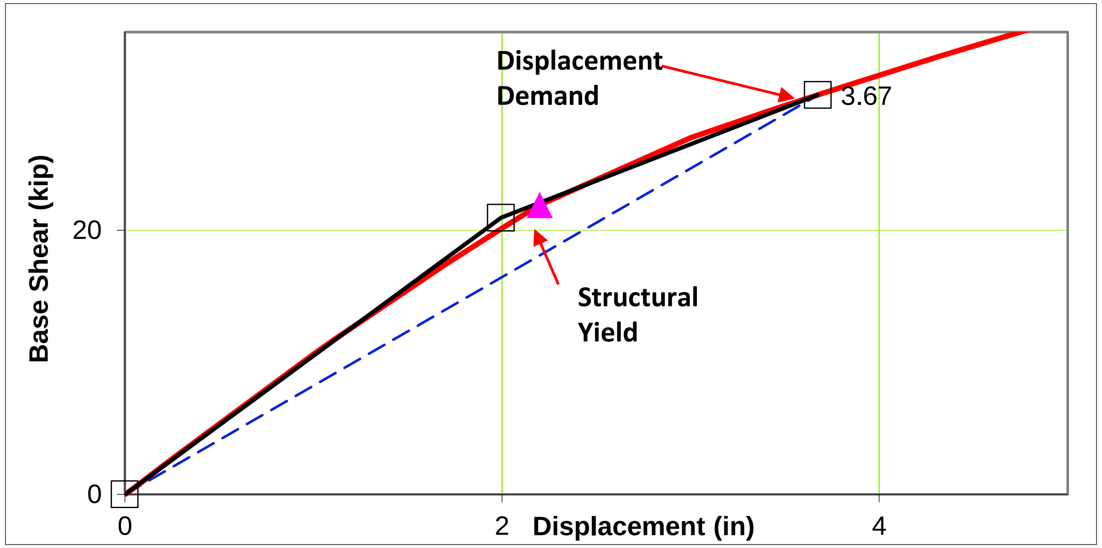
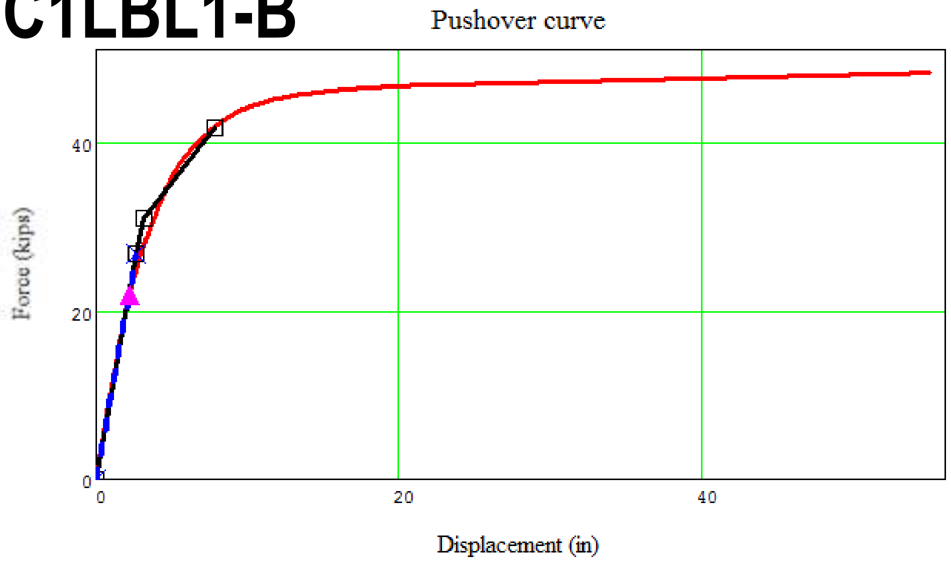
C1LBL1-A

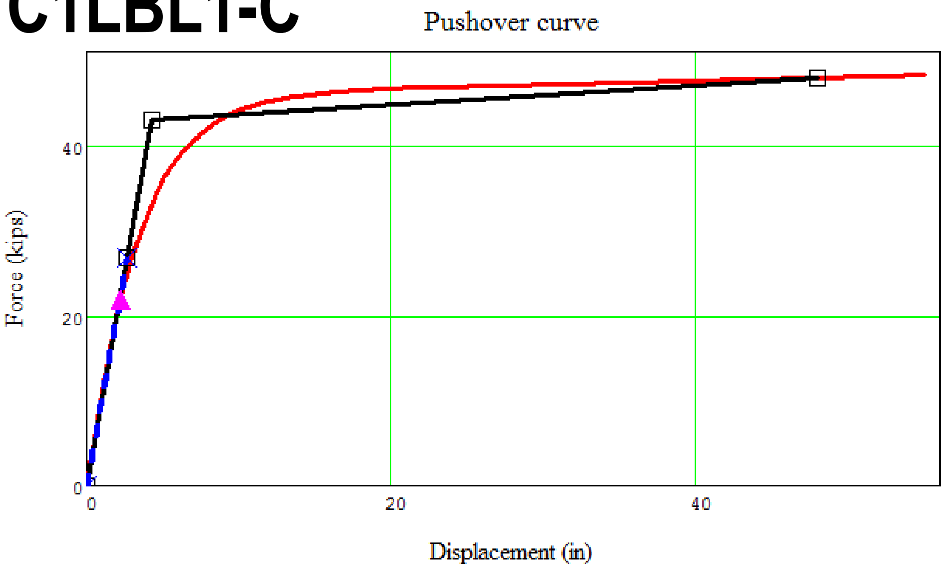




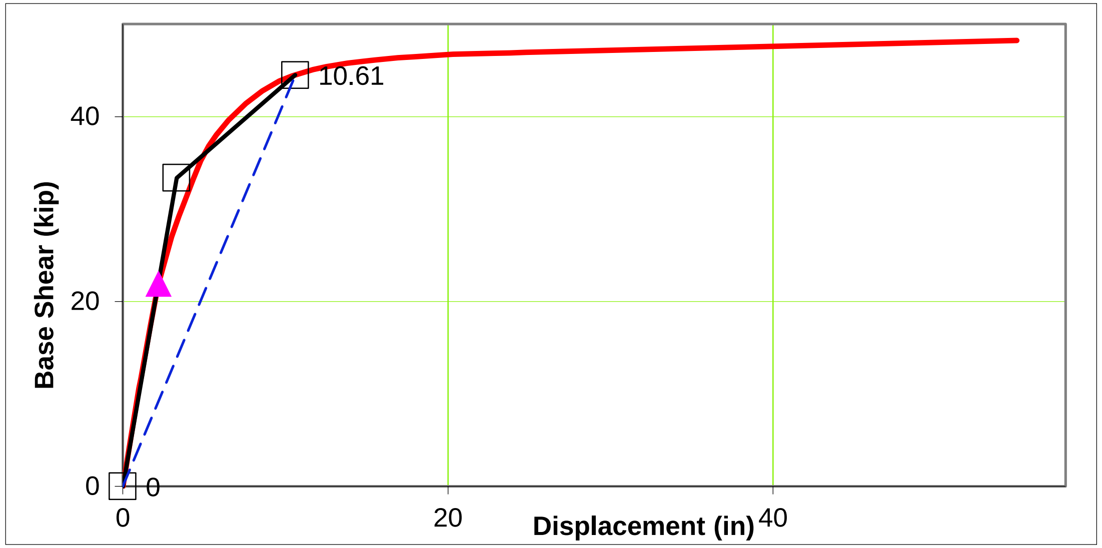
C1LBL1-B

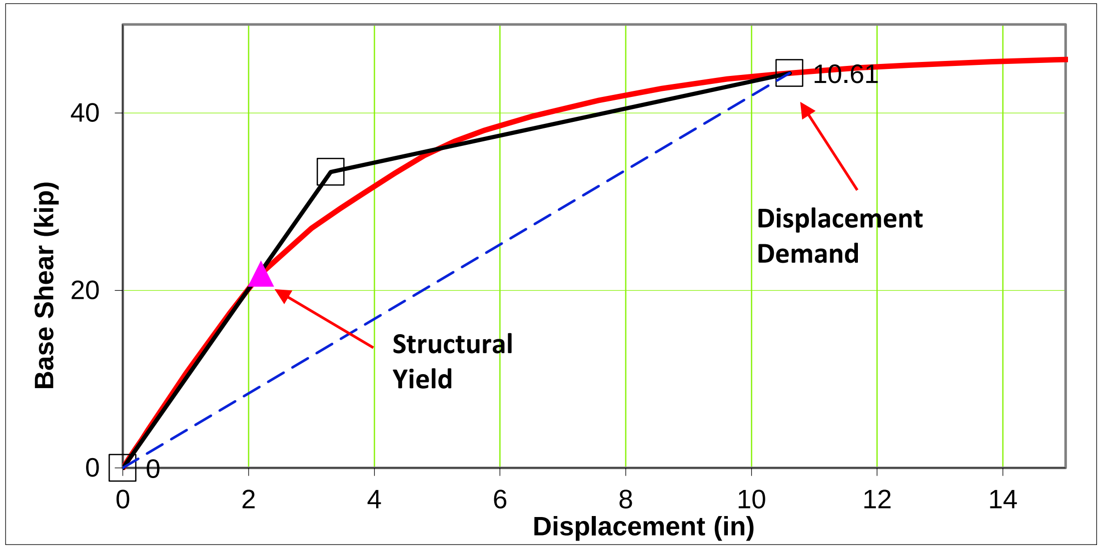


C1LBL1-C



C1LBL2-A





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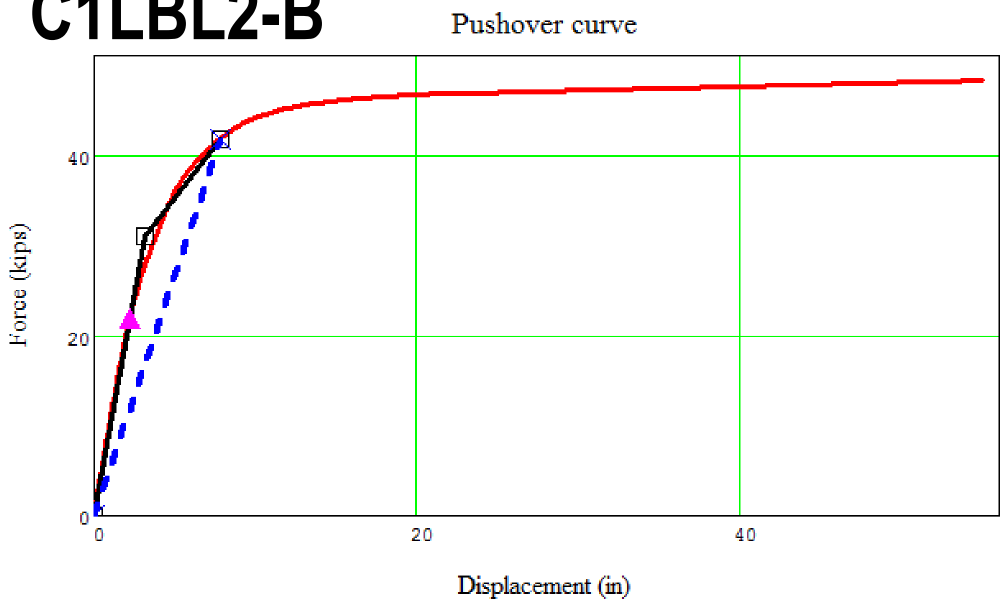
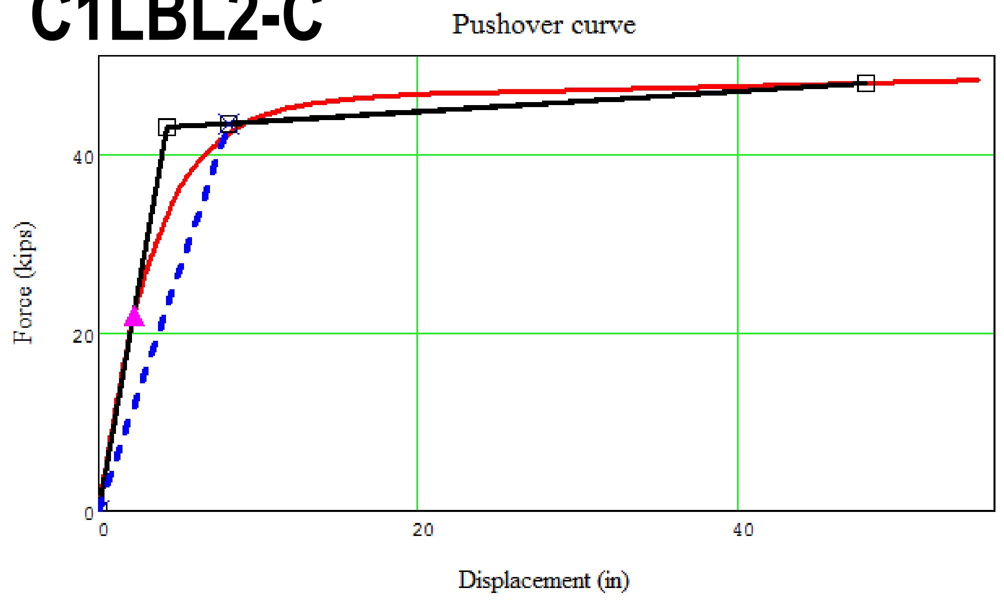
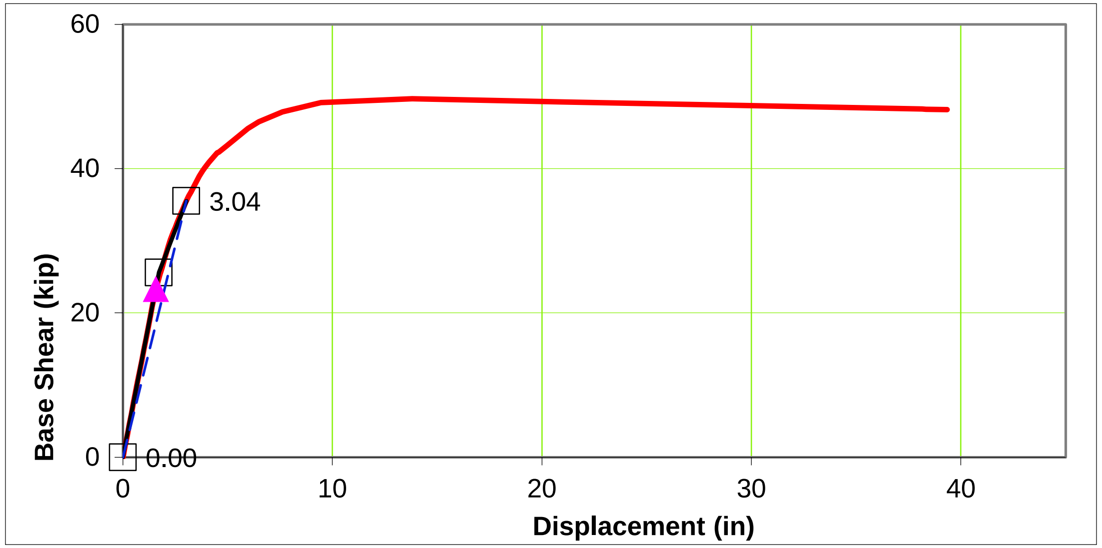
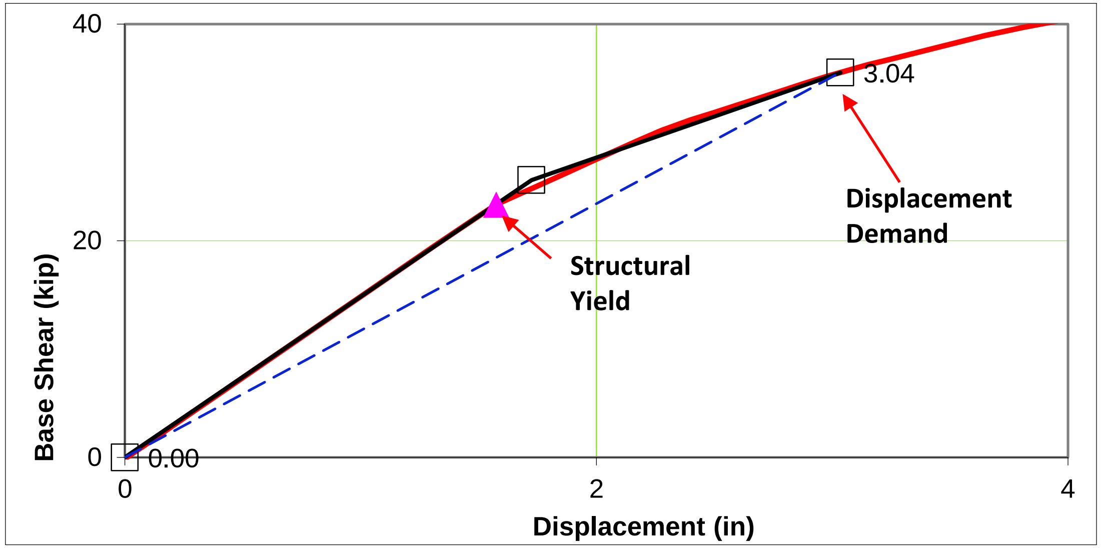


C1LBL2-C

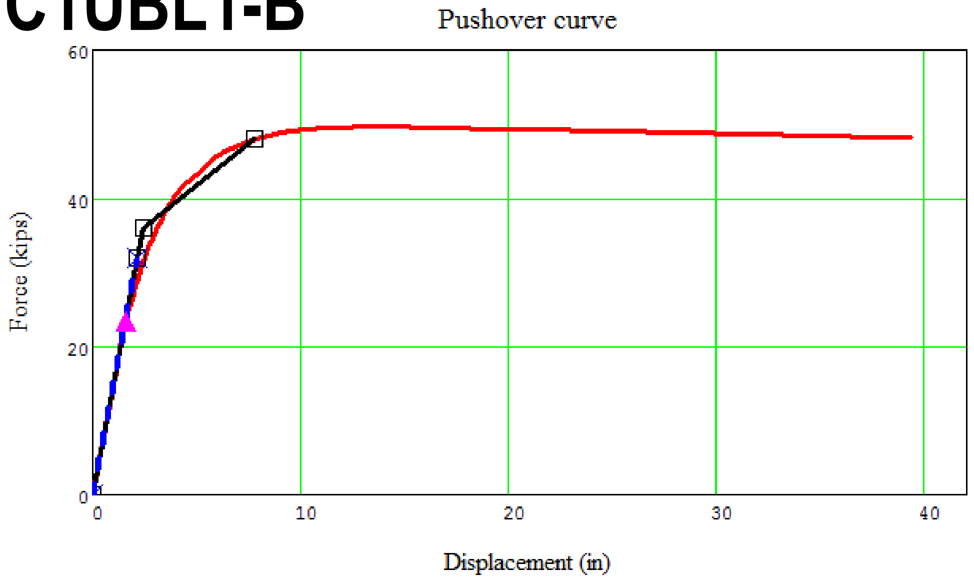


C1UBL1-A

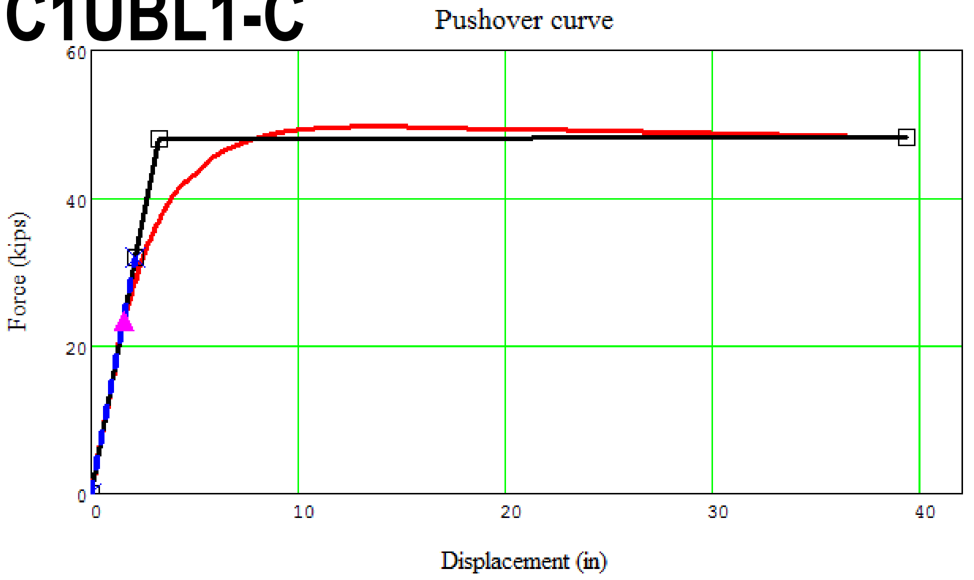




C1UBL1-B



C1UBL1-C



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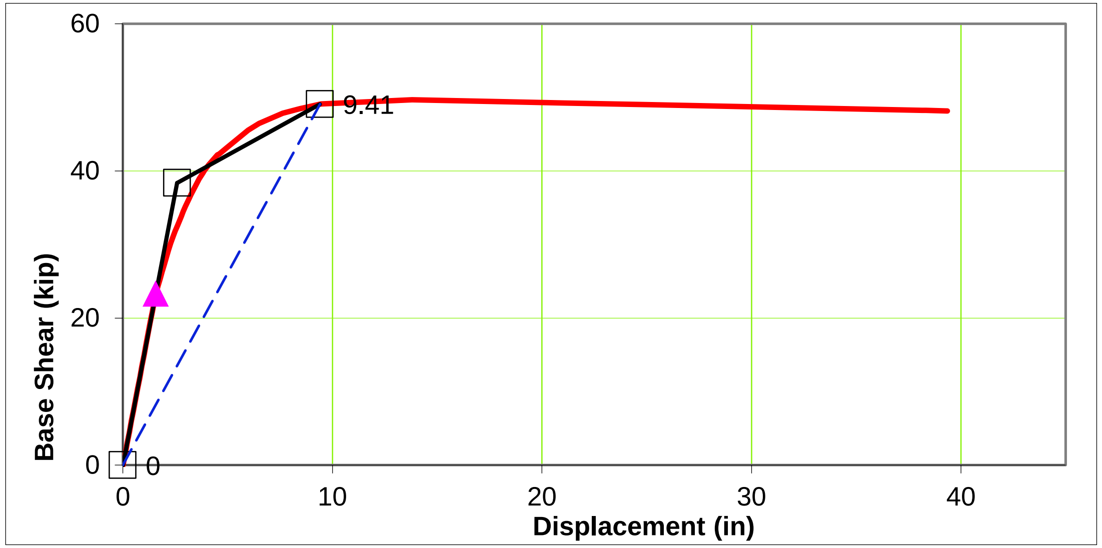
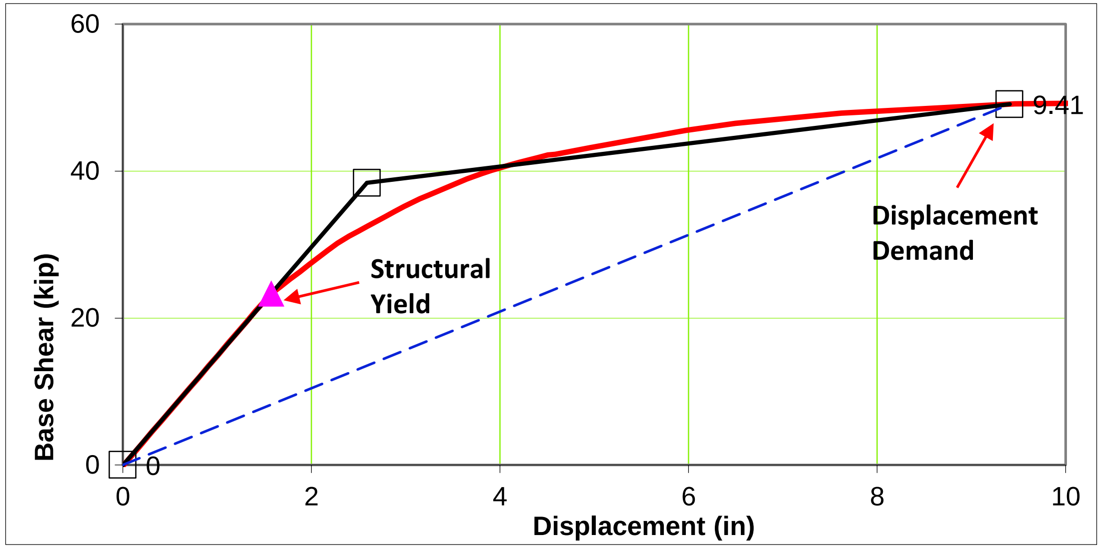
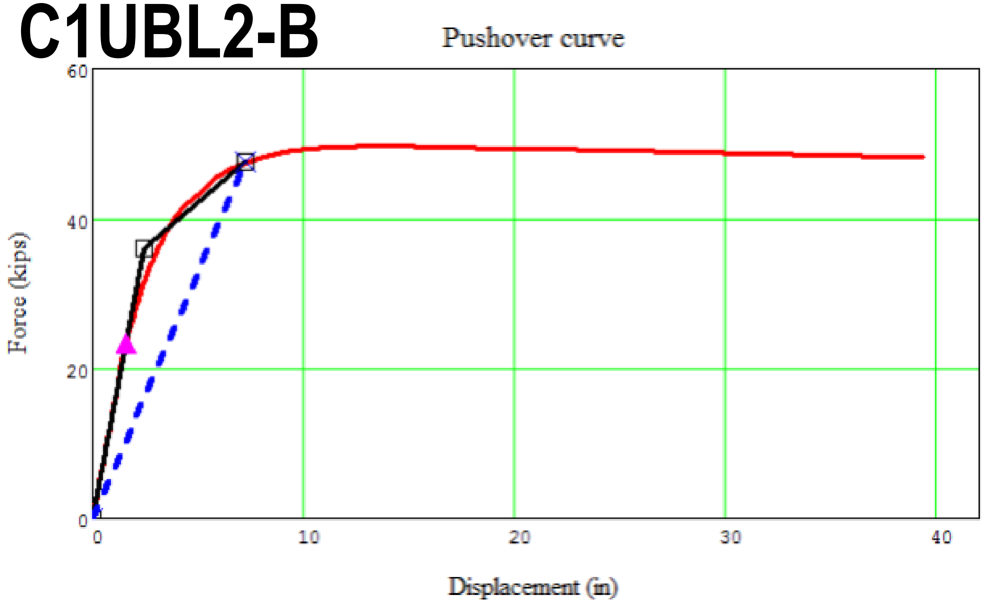
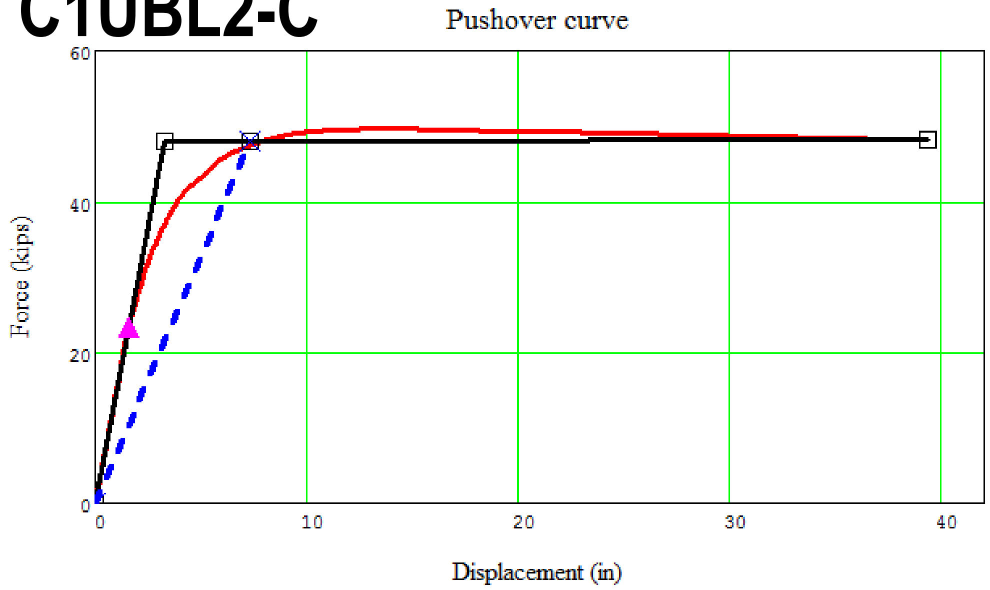




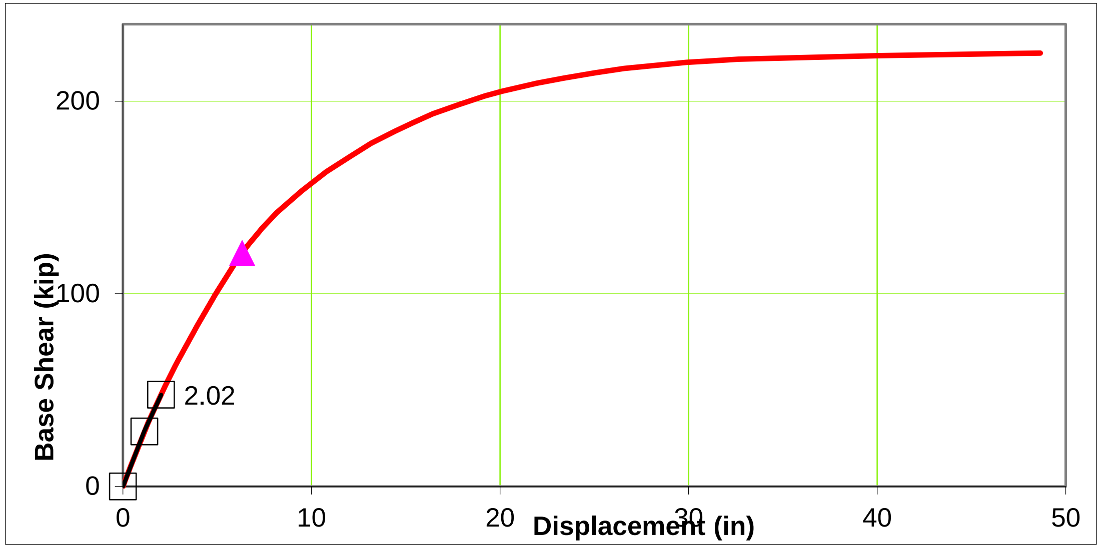
C1UBL2-B

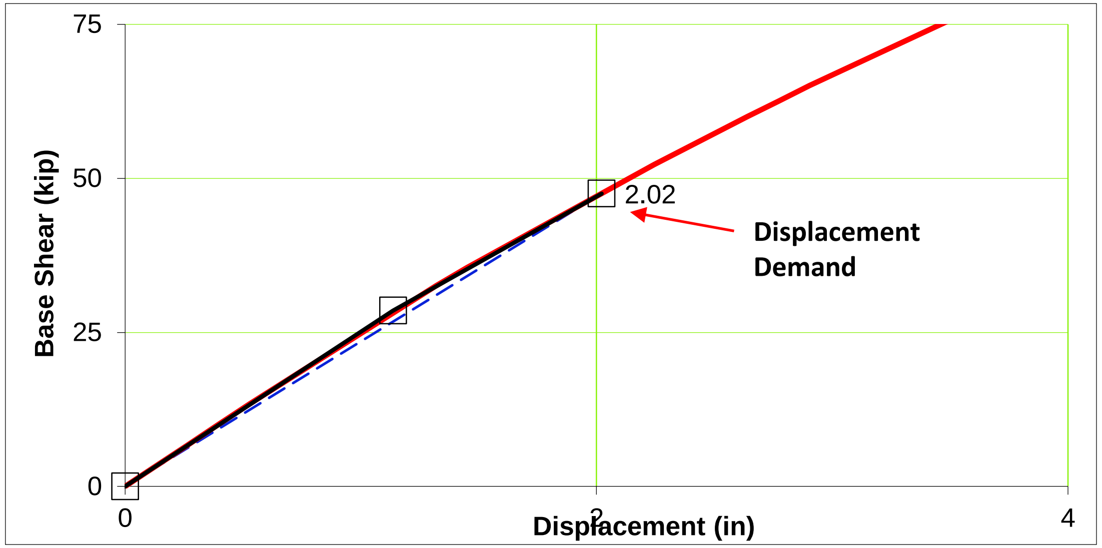


C1UBL2-C



C2LBL1-A





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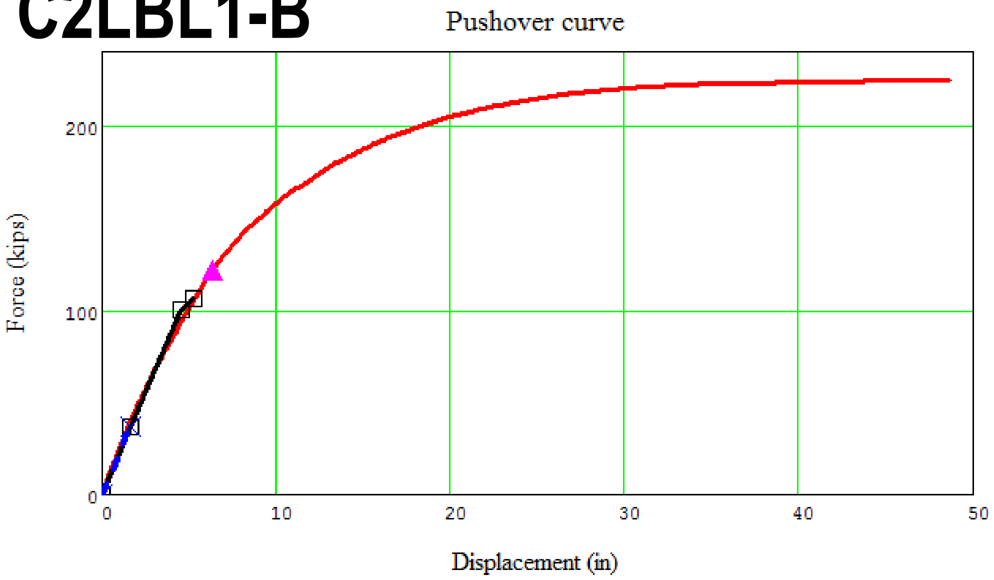
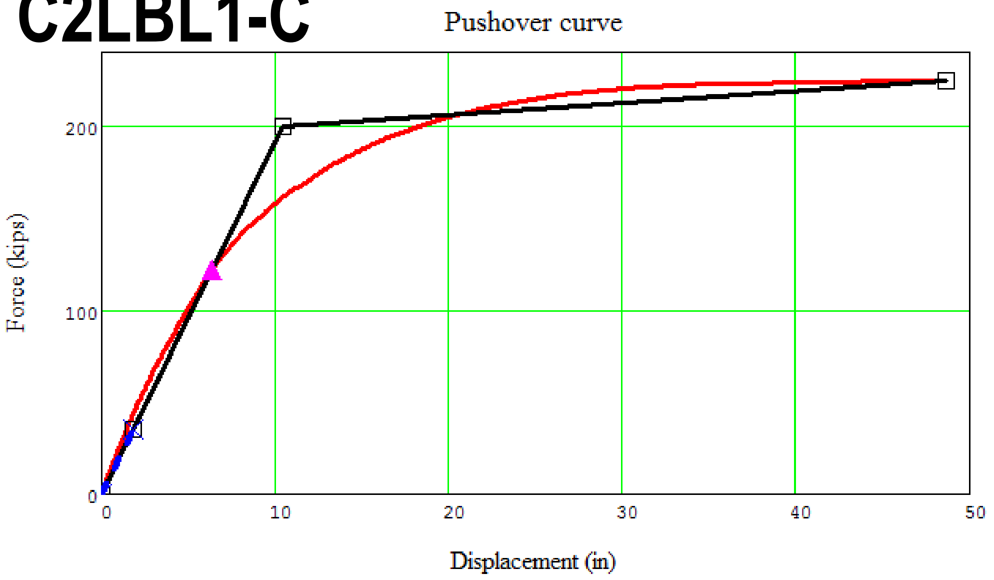


C2LBL1-C



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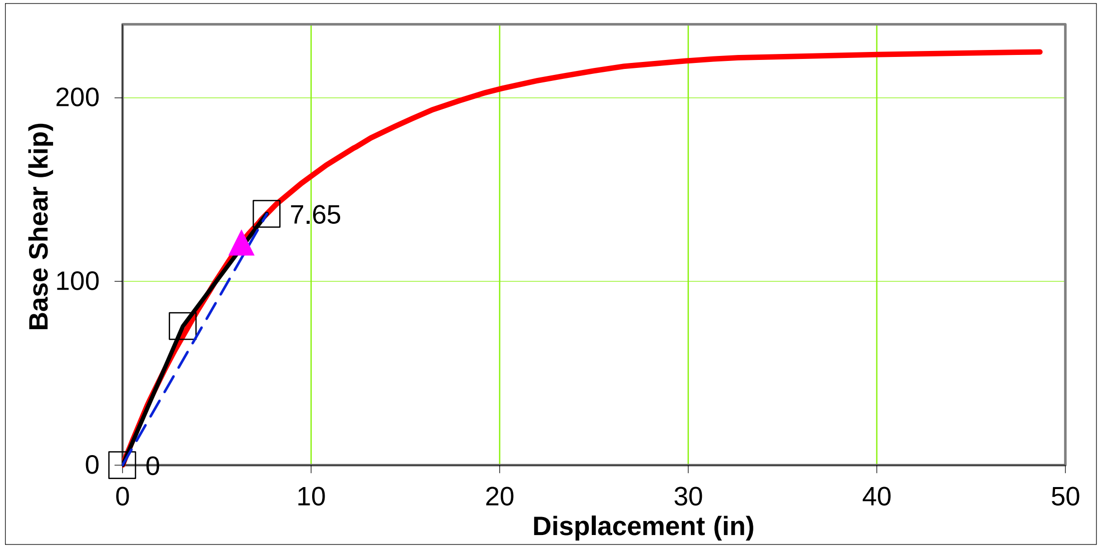
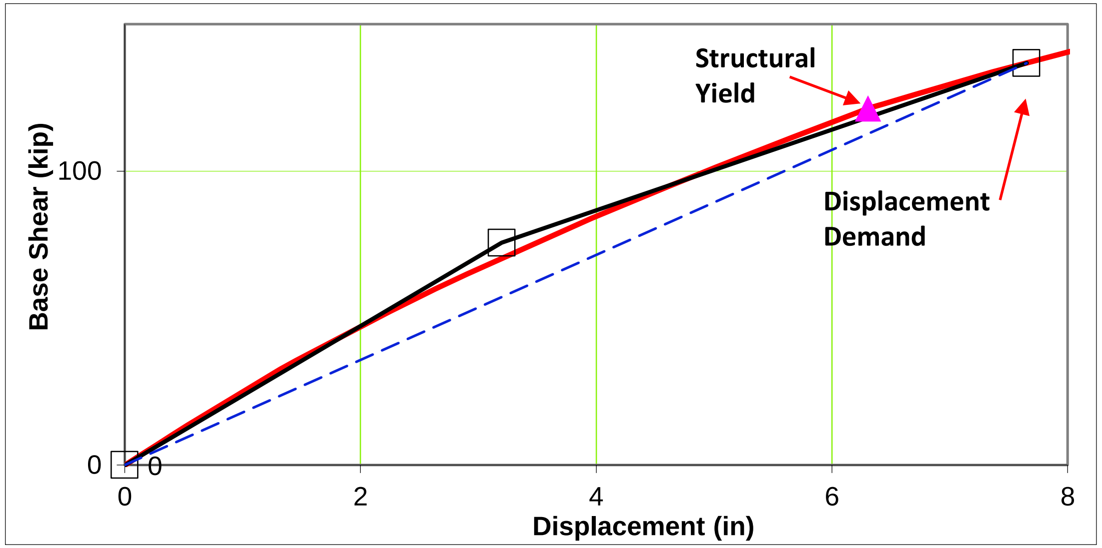
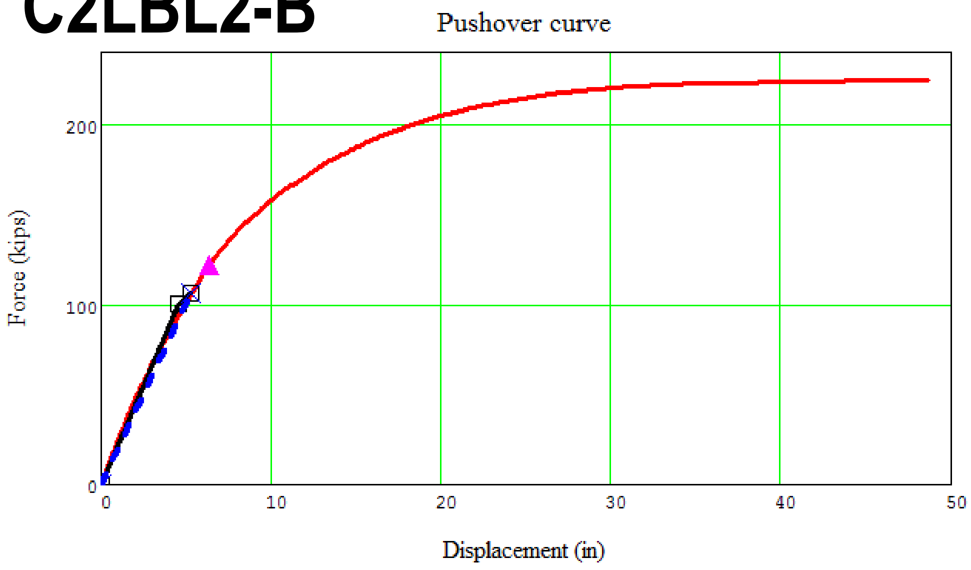




C2LBL2-B



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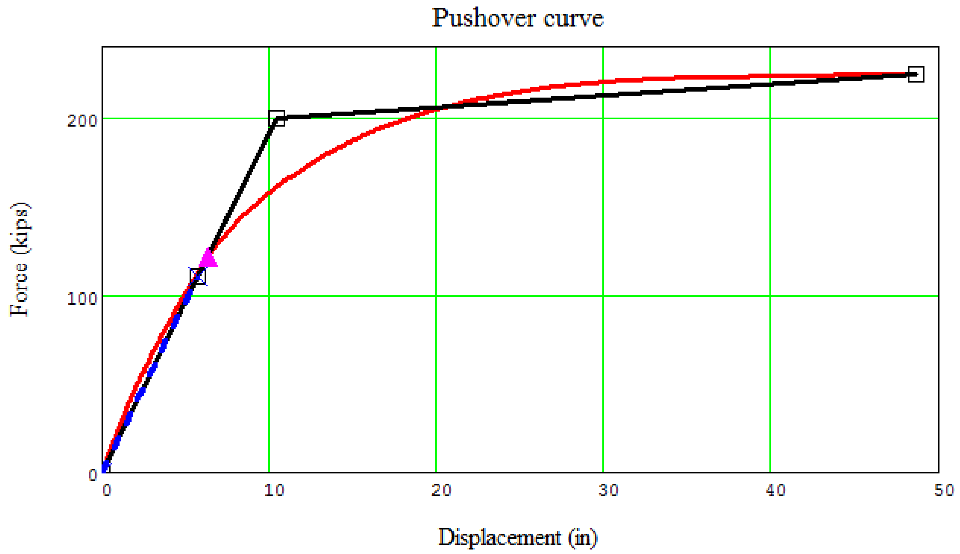

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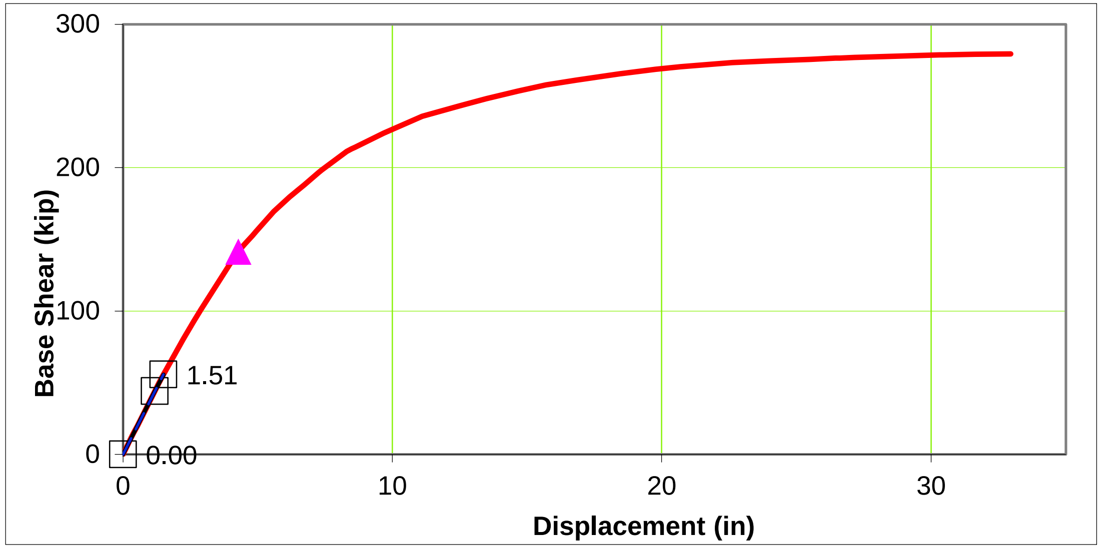
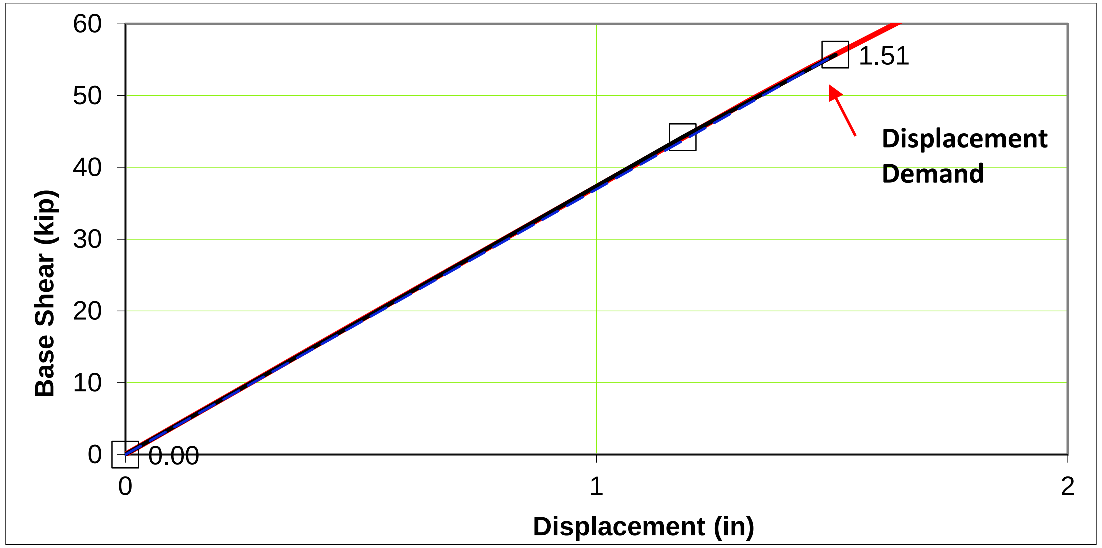
C2UBL1-A





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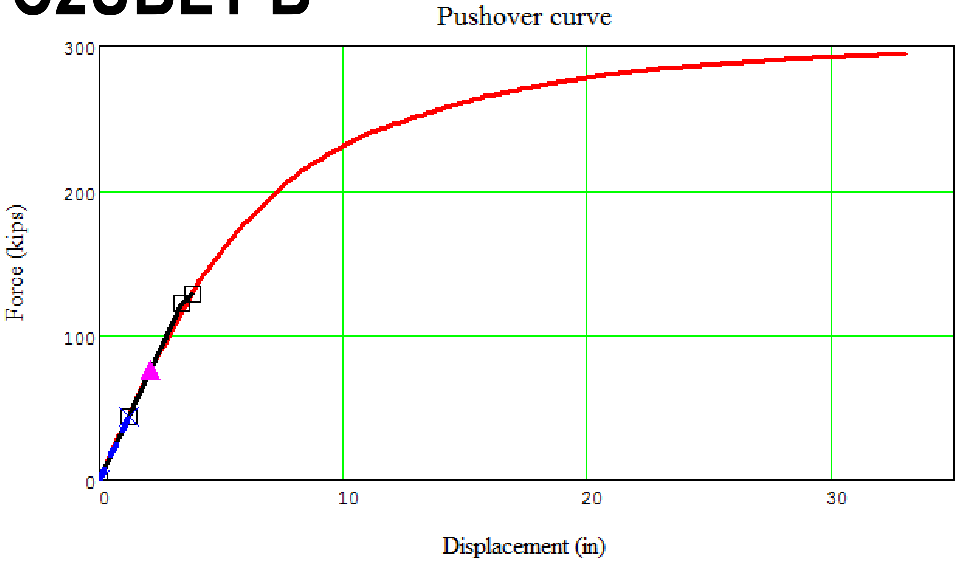
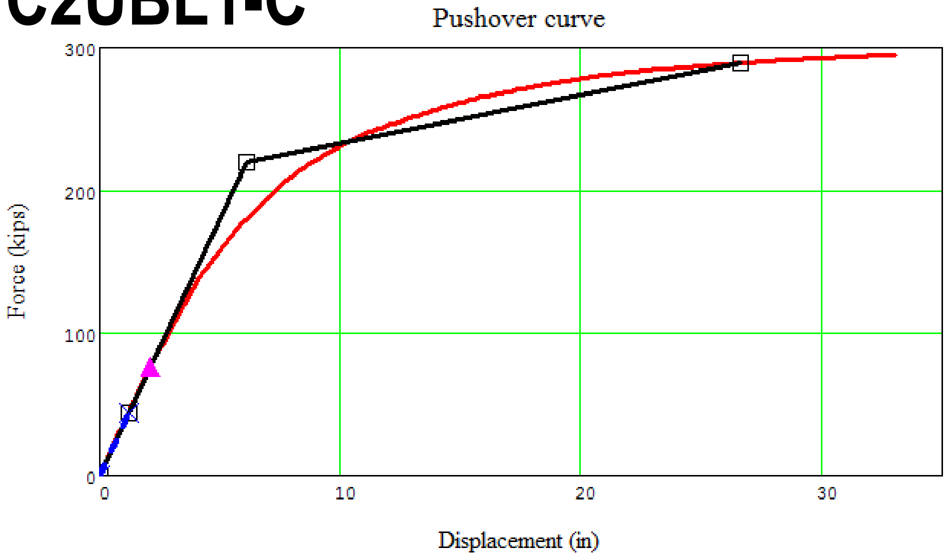


C2UBL1-C



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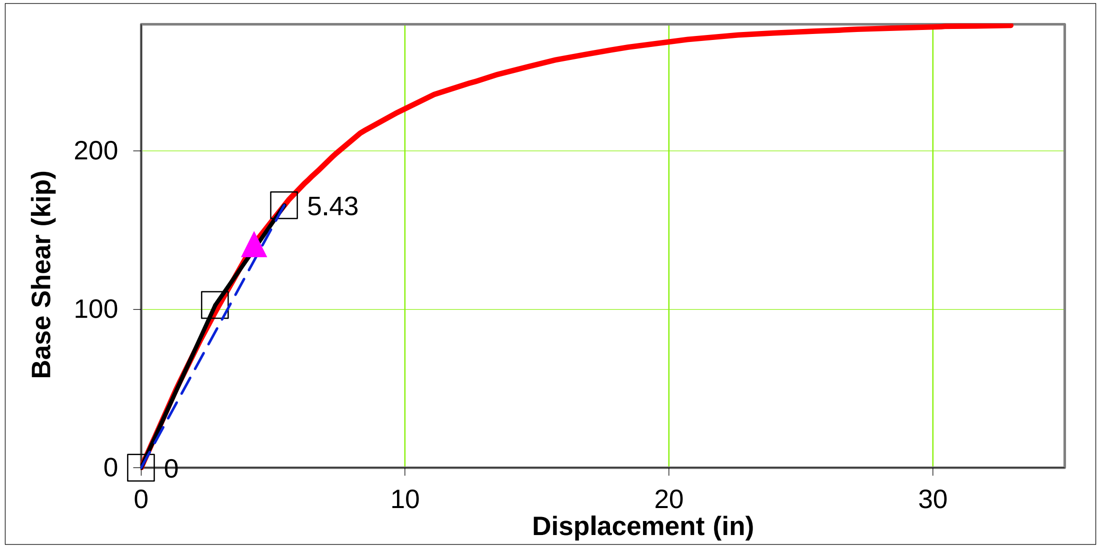
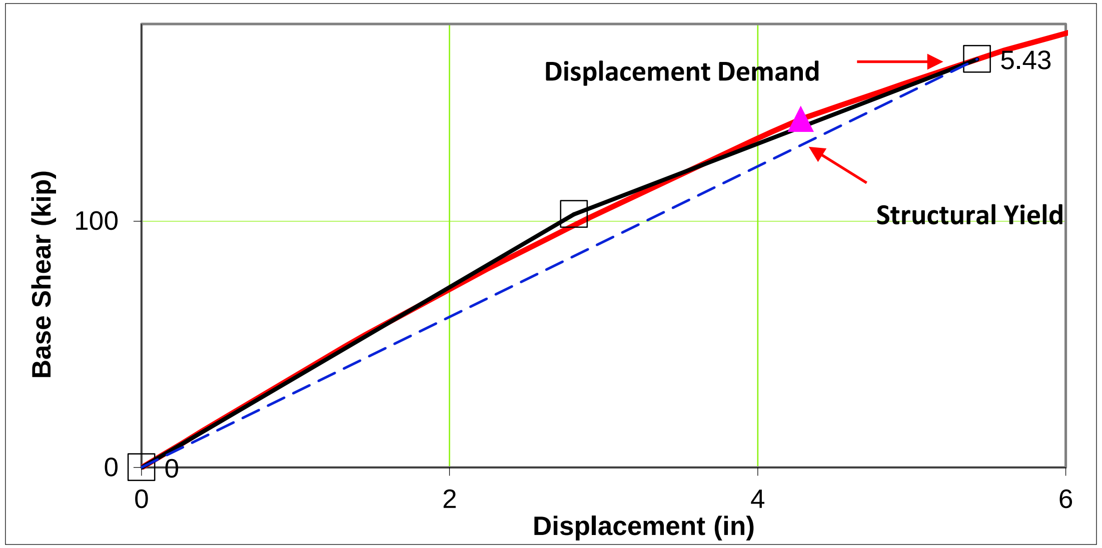
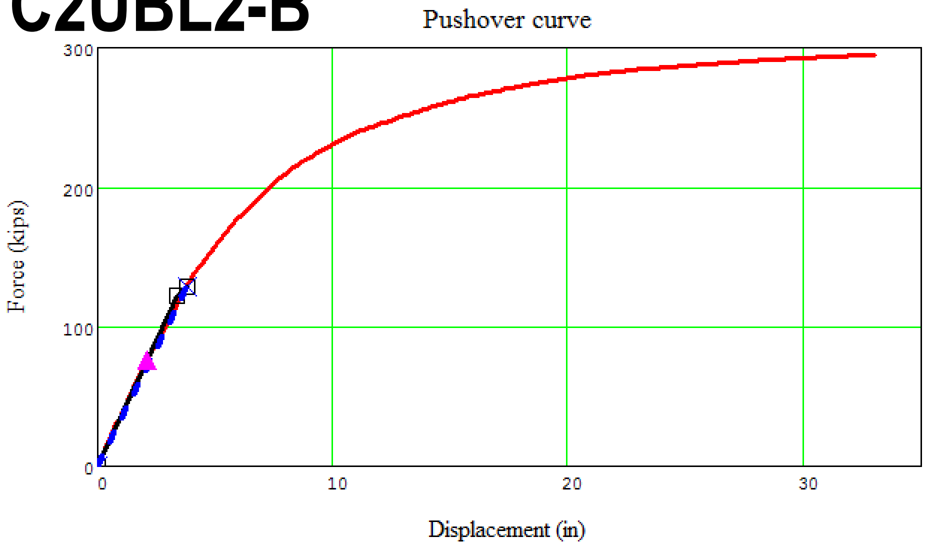
C2UBL2-A

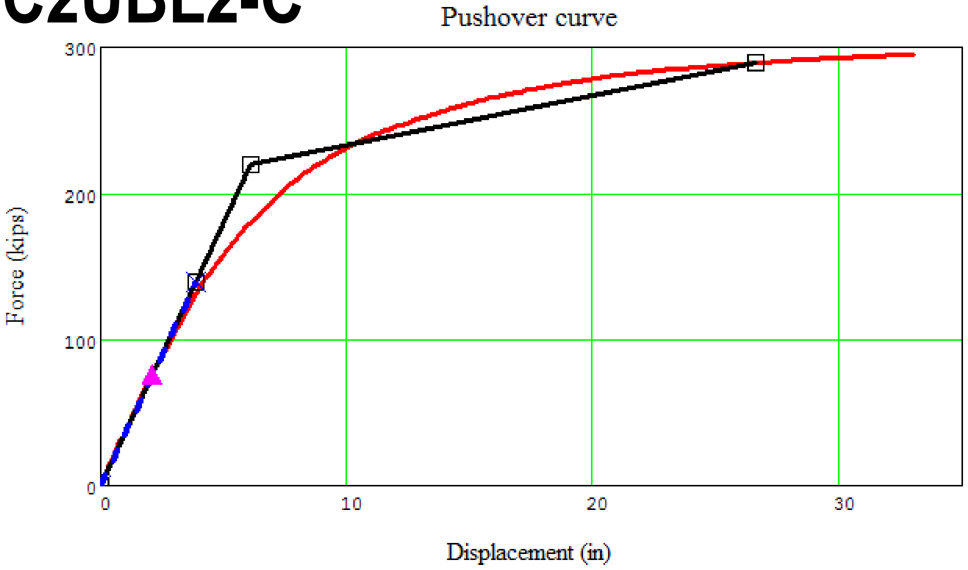




C2UBL2-B



C2UBL2-C



Displacement Demand Summary

Case		MOTEMS				POLA/POLB				Proposed Method			
		LB		UB		LB		UB		LB		UB	
		Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
Case 1	Period (s)	1.66		1.40		1.66		1.40		1.66		1.40	
	First Yield (in)	2.20		1.58		2.20		1.58		2.20		1.58	
	Effective Yield (in)	2.00	3.31	1.72	2.59	3.10	3.10	2.51	2.51	4.31	4.31	3.24	3.24
	Stiffness Ratio "r"	0.53	0.15	0.51	0.11	NA				NA			
	Displacement Demand (in)	3.67	10.61	3.04	9.41	2.68	7.80	2.15	7.25	2.68	8.18	2.15	7.35
	Displacement Ductility	1.84	3.21	1.76	3.63	0.87	2.52	0.86	2.98	0.62	1.90	0.66	2.25
	Effective Damping (%)	5.00	13.10	5.00	15.50	10.00	20.84	10.00	21.96	10.00	18.50	10.40	19.98
Case 2	Period (s)	1.08		0.88		1.08		0.88		1.08		0.88	
	First Yield (in)	6.31		4.28		6.31		4.28		6.31		4.28	
	Effective Yield (in)	1.14	3.20	1.18	2.81	4.50	4.50	3.37	3.37	10.40	10.40	6.08	6.08
	Stiffness Ratio "r"	0.85	0.58	0.95	0.66	NA				NA			
	Displacement Demand (in)	2.02	7.65	1.51	5.43	1.65	5.30	1.22	3.81	1.81	5.76	1.21	3.85
	Displacement Ductility	1.78	2.39	1.27	1.93	0.37	1.18	0.36	1.13	0.17	0.55	0.20	0.63
	Effective Damping (%)	5.00	5.00	5.00	5.00	10.00	12.72	10.00	12.07	10.00	10.00	10.00	10.00

Conclusions

- Twenty four cases were analyzed to evaluate three approaches for structural damping
- The displacement at first yield is not dependent on the analysis approach
- System effective yield displacement is dependent on the analysis approach
- Effective damping for MOTEMS ranged from 5% to 15% and the other two approaches ranged from 10% to 22%
- Displacement demand for MOTEMS was conservatively larger than the proposed approach by 12% to 41%
- Displacement demand for POLA/ POLB was lower than the proposed approach by a maximum of 9% and in other cases it matched the proposed approach

Conclusions

- Effective damping, ξ_{eff}, is function of displacement ductility, μ_{Δ}, structure type, and soil condition
- Its difficult to define one equation for all types of structures
- MOTEMS and POLA/POLB damping equations do not have specified minimum values
- The proposed approach is a practical method

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