ATC-116-4

Solutions of the Issue of Short-Period Building Performance

Preliminary Investigation of the C_d Factor

(period-dependence based on studies of light-frame wood buildings)

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Investigation of the C_d Factor
Background - Initial Position Paper

- **PUC Proposals (C_d = R).** Proposed changes to C_d factor (IT2-4 and IT2-5) would effectively set C_d = R for structural separation (Section 12.12.3) and deformation compatibility (Section 12.12.5) consistent with the existing requirements of Section 12.12.4.
- **PUC Concerns.** Negatives by PUC included the following:

  (1) Proposals are not universal (i.e., C_d = R concept should be proposed in all applicable sections)

  (2) Proposals ignore additional amplification at short periods (e.g., C_d > R when $T < T_s$).

  (3) Proposals ignore influence of damping when damping is not equal to 5 percent of critical (e.g., $C_d = R/B_I$ where B_I is the effective damping coefficient of the system of interest, at or just below yield).

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- **Include Damping (?)**. Include (explicitly), include (implicitly with ductility) or ignore (system-dependent) damping?
- **Include Short-Period Amplification (?)**. Include or ignore additional peak nonlinear response amplification at short periods?
- **Response Amplitude (?)**. At what response amplitude should peak nonlinear response be estimated (e.g., Design Earthquake (DE), MCE or point of incipient collapse)?
- **Nonlinear Response (?).** Should (how should) global estimates of peak nonlinear response be incorporated (explicitly or implicitly) in ELF and RSA design Procedures - e.g., how should global estimates of peak nonlinear response (roof drift) be applied to linear models of the building when the deformed shape of the building at peak inelastic response is significantly different from the elastic deformed shape (e.g., 1st-story drift of a multi-story system with a relatively soft/weak 1st-story)?

Investigation of the C_d Factor
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- **Purpose.** The initial position paper provides background on the dynamic response characteristics that influence peak earthquake displacement of buildings and other structures, in particular, the ratio of peak nonlinear (inelastic) response to (linear) elastic response as characterized by 5%-damped response spectra.

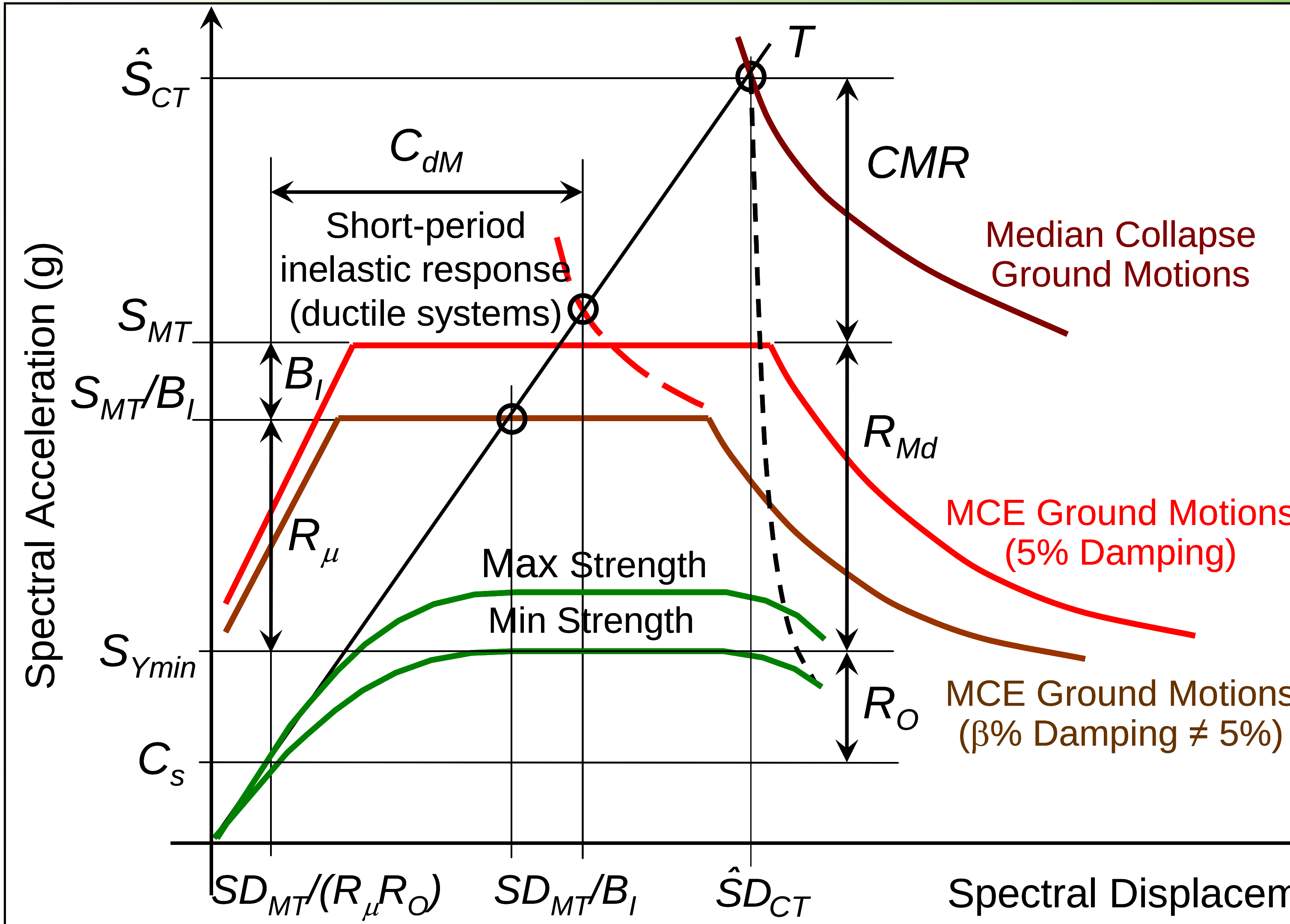
  The intent of this work is to provide the PUC with the requisite technical information to make an informed decision about the subject proposals (possibly with modification).

- **Approach.** The paper develops a notional formula for the C_d factor that incorporates additional amplification at short periods and effective damping (B_I) such that simpler and approximate definitions of C_d (e.g., $C_d = R$) can be evaluated against more accurate measures of peak building response.

Investigation of the C_d Factor Background - Initial Position Paper

- **NIST GCR 12-917-20**. The notional formula of the C_d factor is based on the recommendations of Chapter 4 of the *Tentative Framework for Development of Advanced Seismic Criteria for New Buildings*, NIST GCR 12-917-20 (NIST 2012) developed by the ATC-84 Project and
- **FEMA P-695**. Section 7.7 of *Quantification of Building Seismic Performance Factors*, FEMA P-695 (FEMA 2009) which specified the value of C_d in terms of system-specific values of effective damping (i.e.,$C_d = R/B_I$, where values of B_I are based on effective damping, β_I, of the structure at or just below yield of the SFRS, Chapter 18, ASCE 7).

Notional Relationship of CMR and Code Design Parameters
(Figure 4-1, NIST GCR 12-917-20)



$$CMR = \frac{\hat{S}_{CT}}{S_{MT}}$$

$$R_M = R_{Md} R_O$$

$$R_O = \frac{S_{Ymin}}{C_s}$$

$$R_{Md} = R_\mu B_I$$

$$R_\mu = \frac{S_{MT} / B_I}{S_Y}$$

$$C_{dM} \geq R_\mu R_O$$

Notional Components of the C_d Factor
(NIST GCR 12-917-20)

- Components of R and C_d Factors:

$$R = R_d \, R_O$$

$$R_d = R_\mu \, B_I$$

$$\mathbf{R = R_\mu \, B_I \, R_O}$$

$$\mathbf{C_d = C_{ds} R / B_I \qquad (\geq R_\mu \, R_O)}$$

Where:

R = Response modification factor.

R_d = Component of the R factor related to total system ductility and damping.

R_μ = Component of the R_d factor related to system ductility.

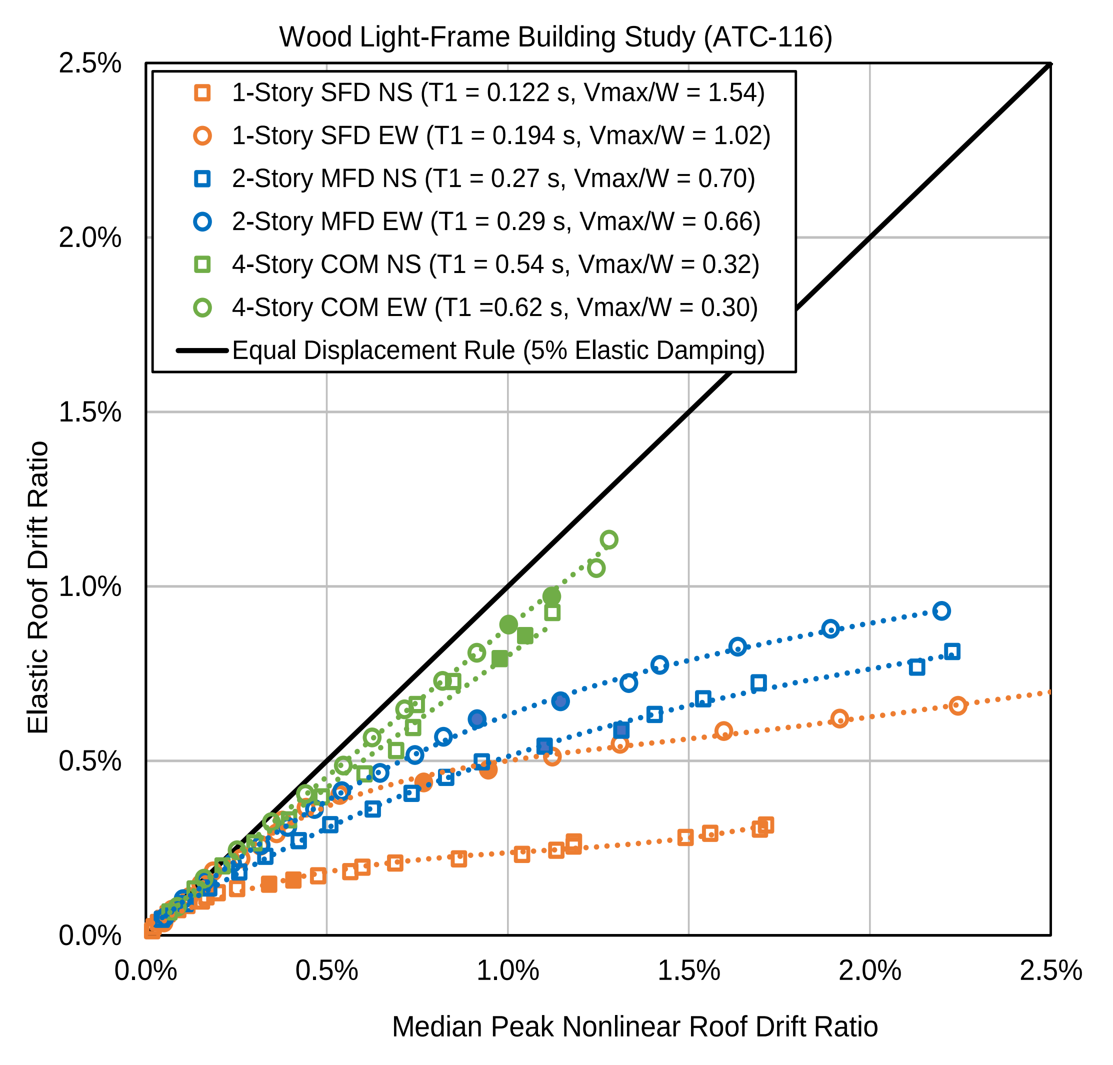
B_I = Component of the R_d factor related to effective system damping, β_I, as set forth in Table 18.7-1 of ASCE 7-16.

β_I = Component of effective damping (including hysteretic energy dissipation) of the structure due to inherent dissipation of energy by elements of the structure, at or just below the effective yield displacement of the seismic-force-resisting system (Section 18.7.3.2.1 of ASCE 7-16).

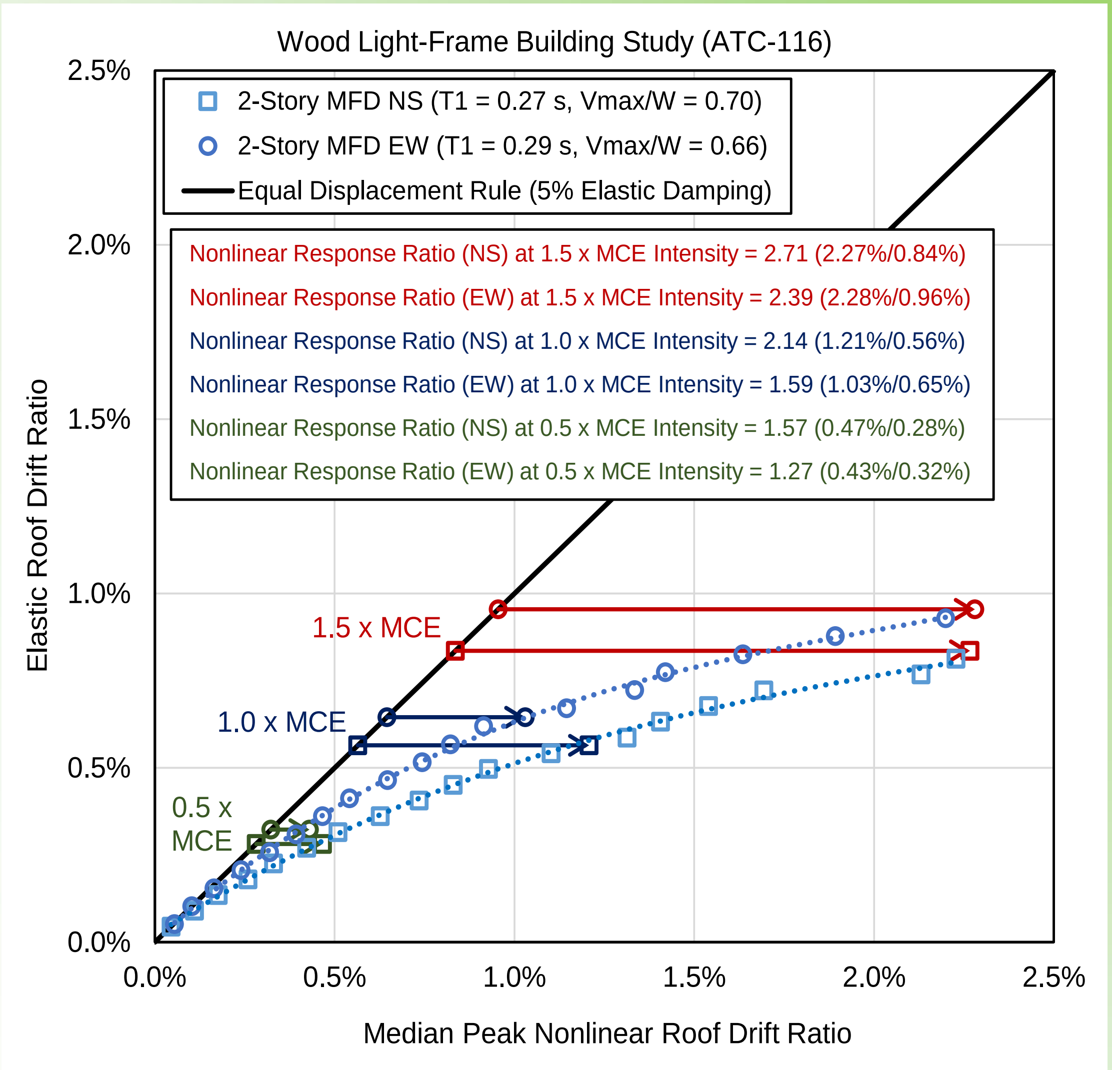
C_d = Deflection amplification factor (see also Section 4.4.5 of NIST GCR 12-917-20).

C_{ds} = Component of the C_d factor associated with additional short-period inelastic deflection amplification (i.e., C_{ds} = 1.0 for mid/long-period structures).

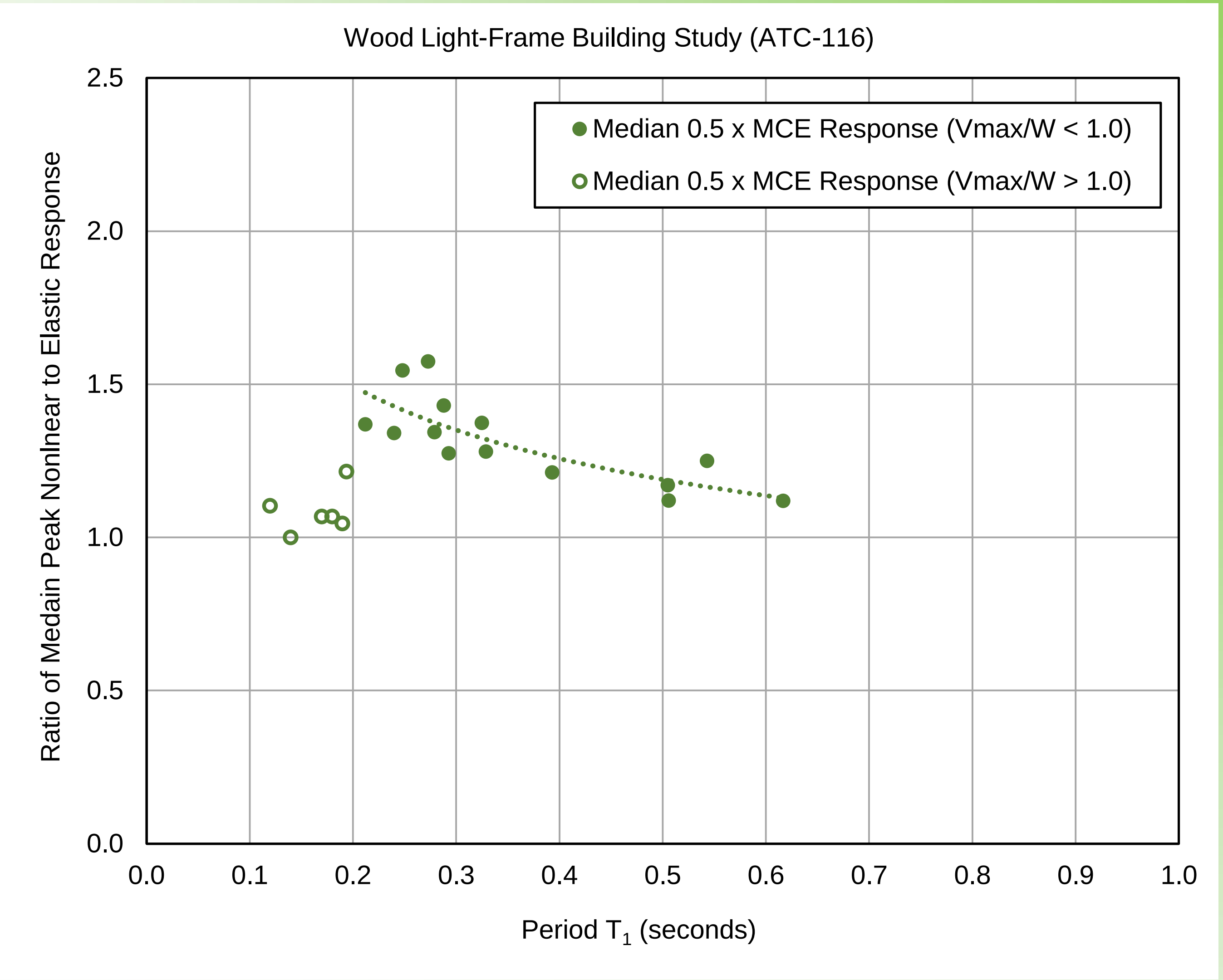
Example plots of median peak nonlinear roof drift ratios of incremental nonlinear dynamic analyses (as a function of the corresponding values of the elastic roof drift ratio) of three wood-light frame archetype models



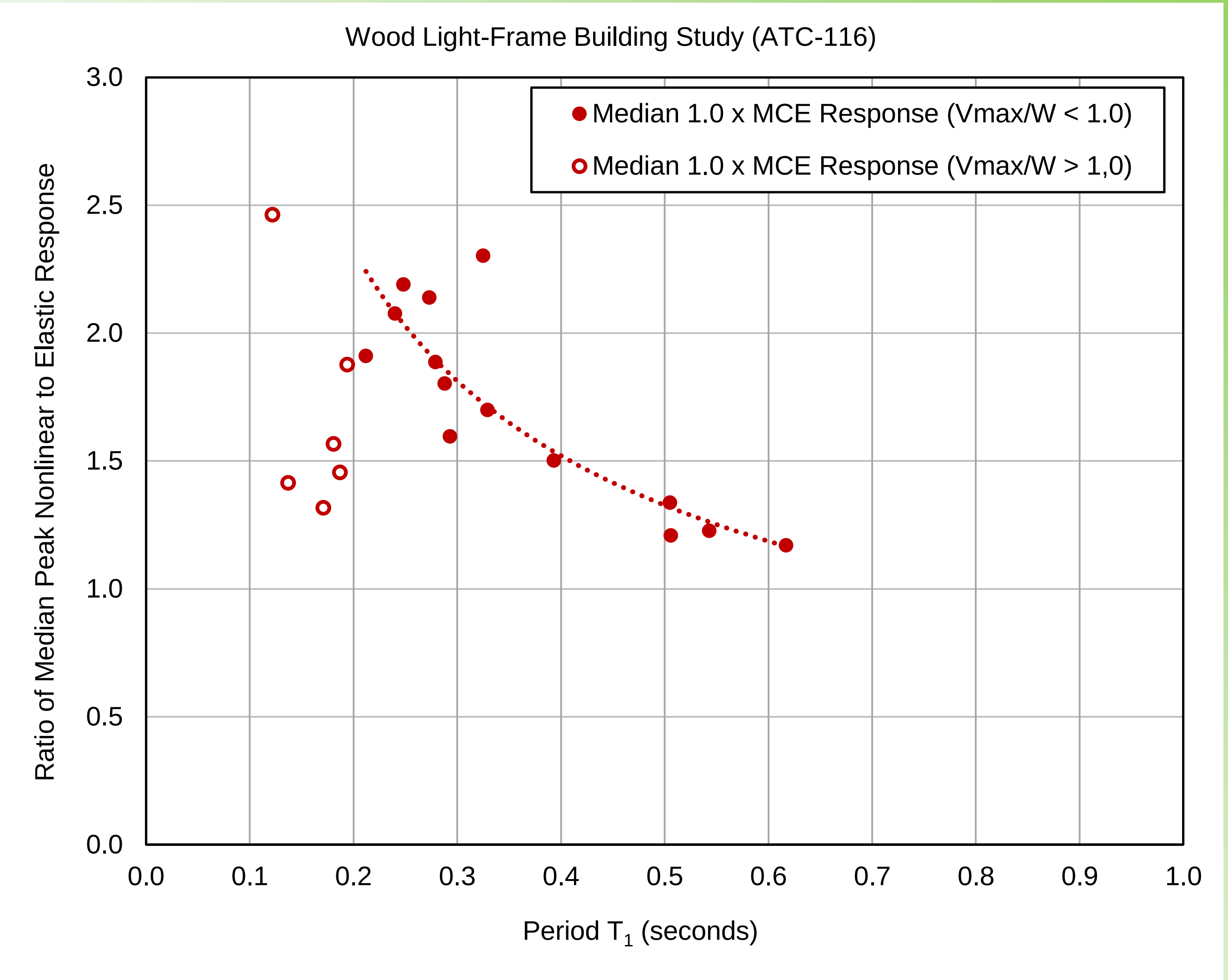
Example plots of median peak nonlinear roof drift ratios of incremental nonlinear dynamic analyses (as a function of the of the corresponding values of the elastic roof drift ratio) of a wood-light frame archetype model of a 2-story multi-family dwelling (MFD) building



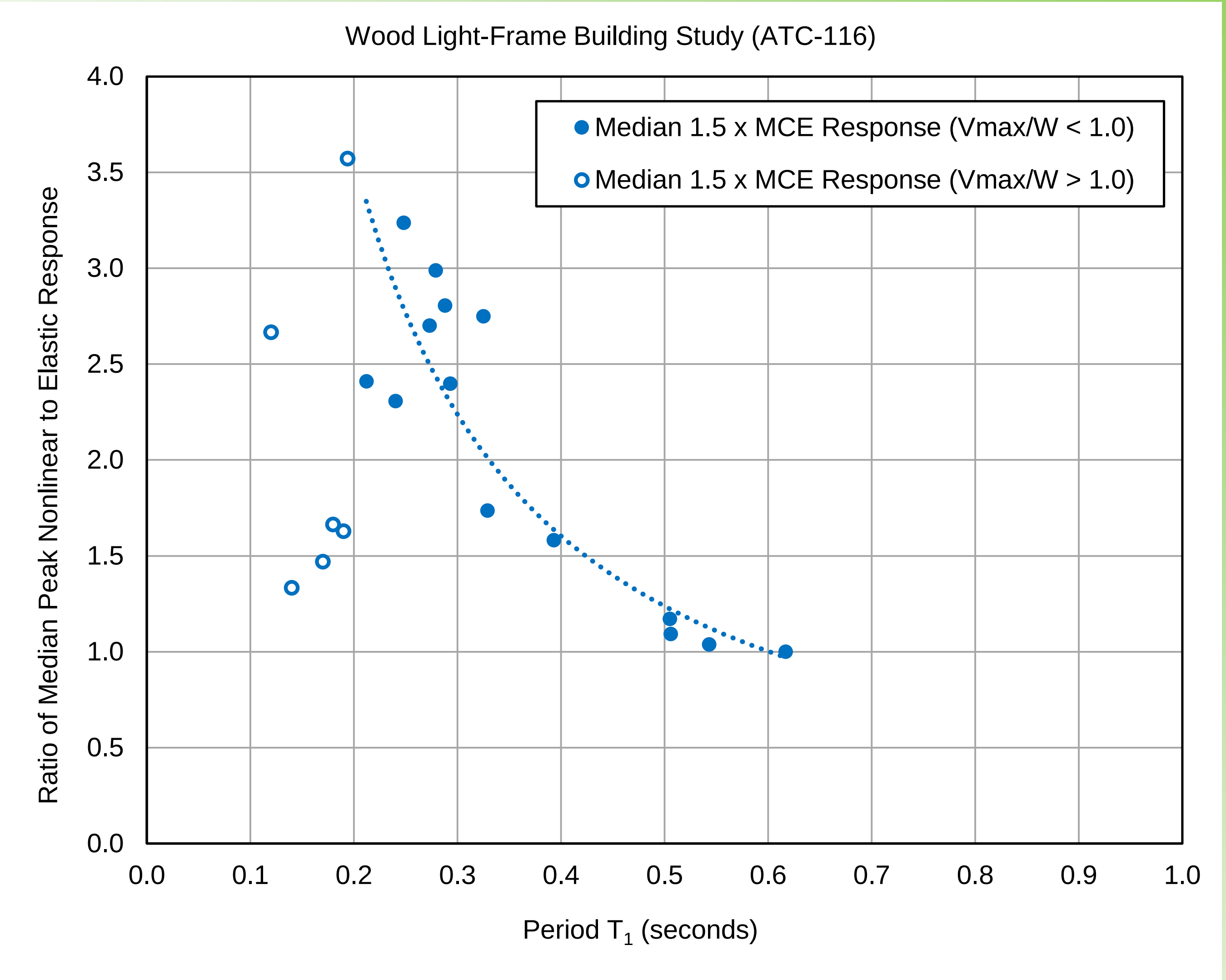
Example plots of the nonlinear response ratio (i.e., ratio of median peak nonlinear roof drift ratios to the elastic roof drift ratio) at 0.5 x MCE (S_{MT} = 0.75 g) intensity as a function of period (T_1)



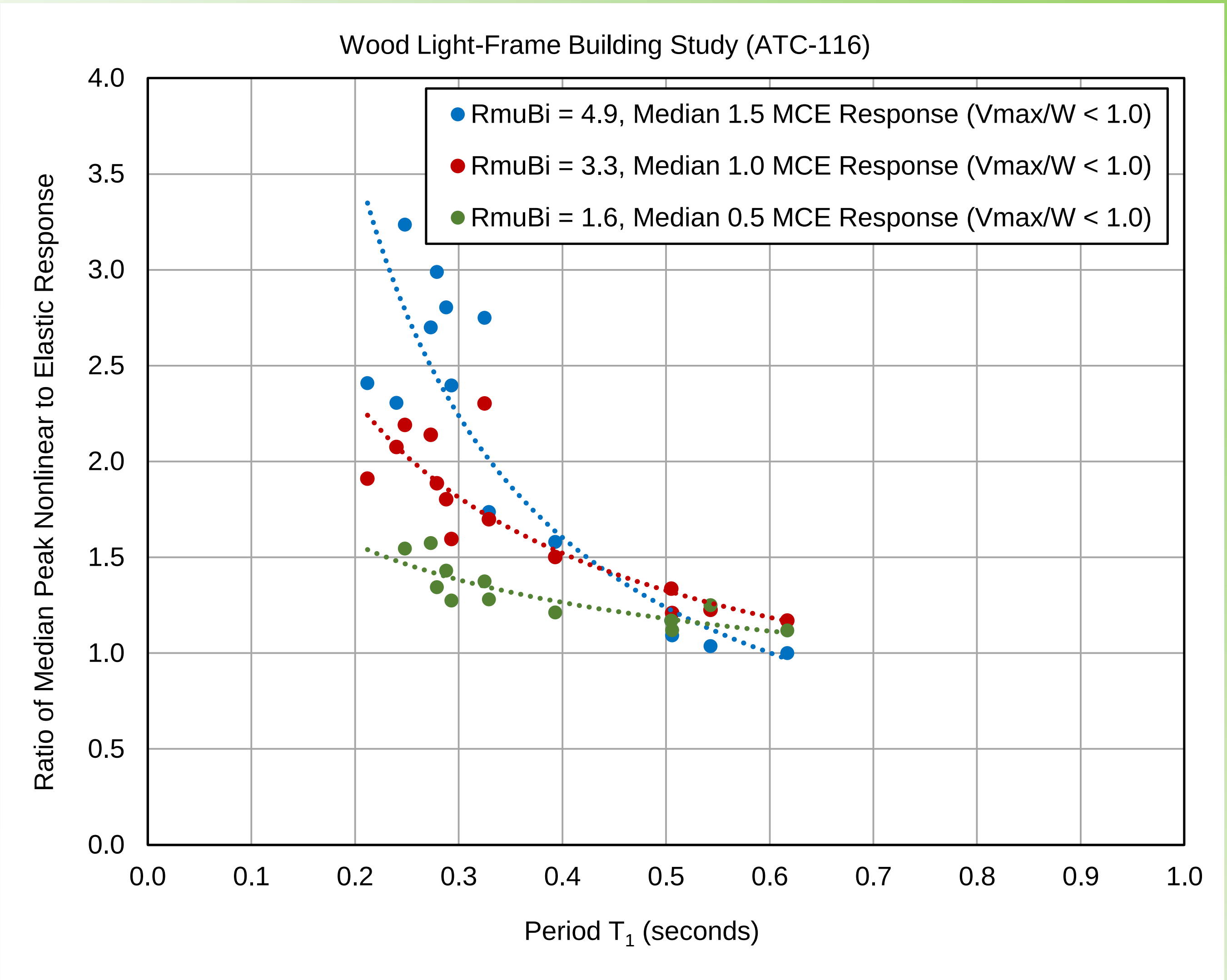
Example plots of the nonlinear response ratio (i.e., ratio of median peak nonlinear roof drift ratios to the elastic roof drift ratio) at 1.0 x MCE (S_{MT} = 1.5 g) intensity as a function of period (T_1)



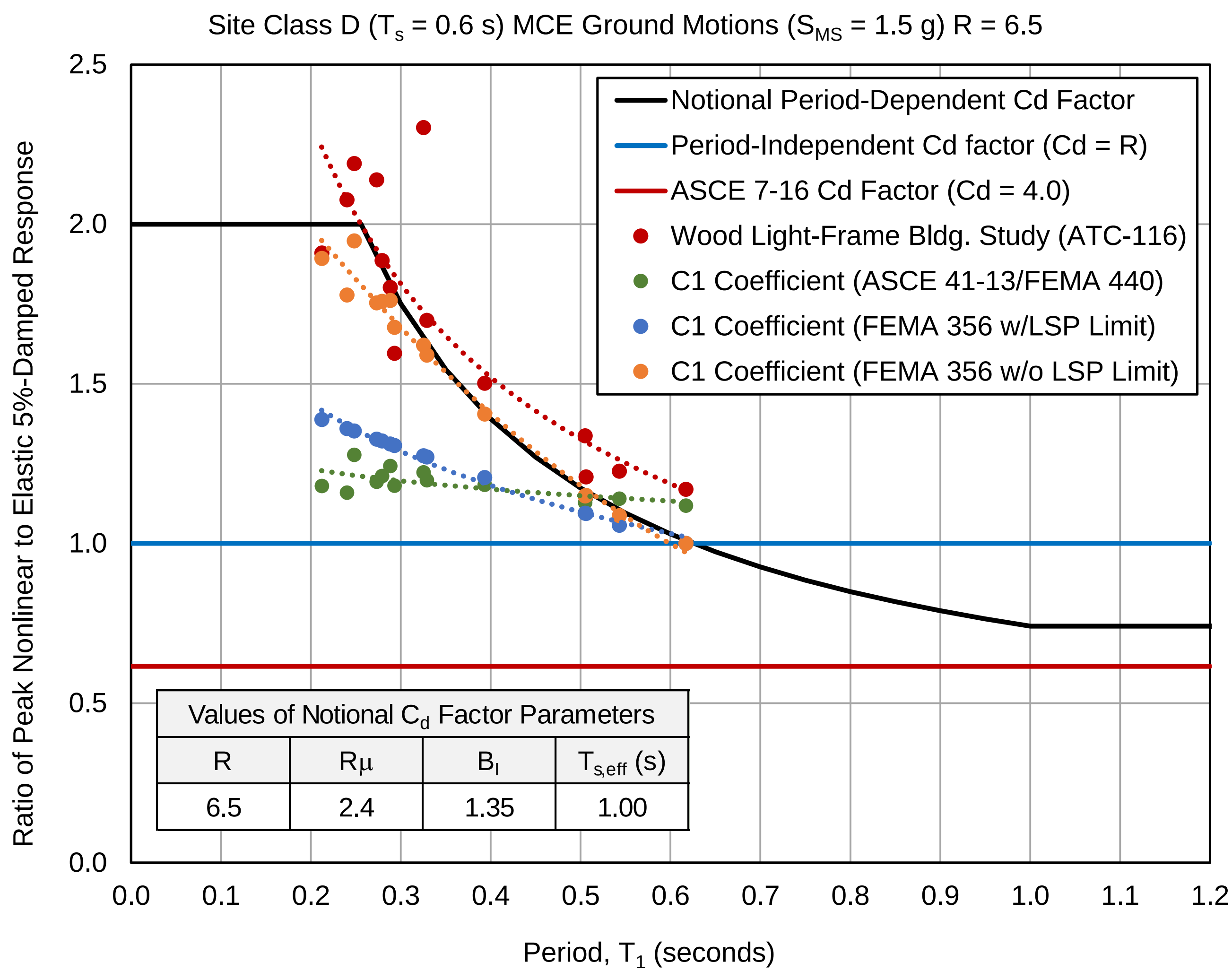
Example plots of the nonlinear response ratio (i.e., ratio of median peak nonlinear roof drift ratios to the elastic roof drift ratio) at 1.5 x MCE (S_{MT} = 2.25 g) intensity as a function of period (T_1)



Example plots of the nonlinear response ratio (i.e., ratio of median peak nonlinear roof drift ratios to the elastic roof drift ratio) at 0.5 x MCE (S_{MT} = 0.75 g), 1.0 x MCE (S_{MT} = 1.5 g) and 1.5 x MCE (S_{MT} = 2.25 g) intensity as a function of period (T_1).



Example plots of the notional period-dependent C_d factor, period-independent C_d factor (C_d = R) and the ASCE 7-16 value of the C_d factor, normalized by R = 6.5, and nonlinear response ratios at 1.0 x MCE (ATC-116) and values of the C_1 coefficient of ASCE 41-13 (FEMA 440) and FEMA 356



Values of Notional C_d Factor Parameters			
R	Rμ	B_I	$T_{s,eff}$ (s)
6.5	2.4	1.35	1.00

Notional Period-Dependent C_d Factor Formula (used in the example)

$C_d = C_{ds}\,(R/B_I)$ Limits: $2.0 \geq C_d \geq 1/B_I$

$C_{ds} = [\{1 + (R_\mu - 1)\} \times \{T_{s,eff}/T\}] / R_\mu$ Limit: $C_{ds} \geq 1.0$ ($T_{s,eff} \geq T_s$)

- The C_{ds} formula uses the functional form of the C_1 parameter of FEMA 356, but extends the short-period range of applicability from T_s to $T_{s,eff}$ (from $T_s = 0.6$ s to $T_{s,eff} = 1.0$ s, in this example)
- R = 6.5 (i.e., wood light-frame system, Table 12.2-1 of ASCE 7-16)
- $R_\mu = R/R_O B_I = 2.4$, where $R_O = 2.0$ (from Table 4-1 of NIST GCR 12-917-20
- $B_I = 1.35$ (from Table 4-4 of NIST GCR 12-917-20).

Questions?