Accounting for ground motion duration and spectral shape in structural design and assessment

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Background and Motivation

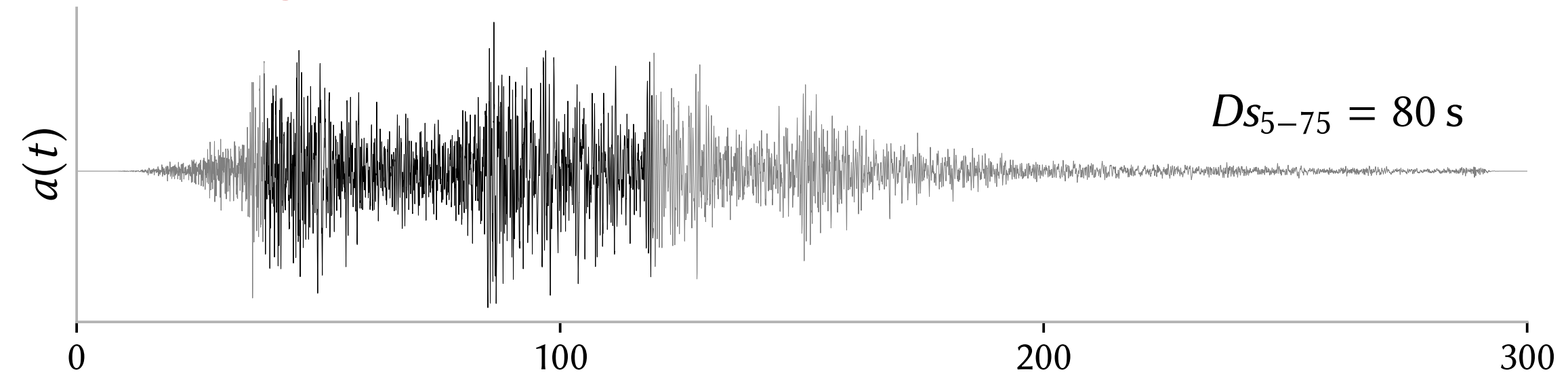
- The equivalent lateral force (ELF) procedure is the most widely used structural design procedure in practice today
- This procedure considers only the $S_a(T_1)$ of the anticipated ground motions, while ignoring their durations and response spectral shapes
- Recent studies by the authors and others have, however, demonstrated that both duration and spectral shape significantly influence structural collapse capacity

Objectives

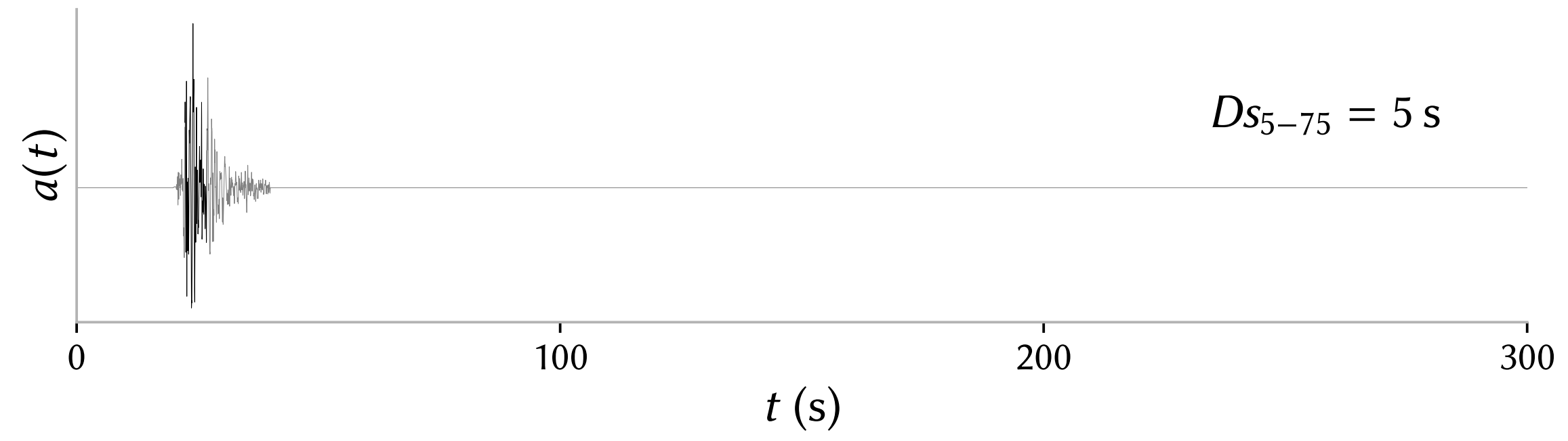
- Develop a framework to characterise the influence of duration and spectral shape on structural collapse risk
- Propose a method to account for the effects of duration and spectral shape in the ELF structural design procedure

Examples of long and short duration ground motions

Long duration record from 2011 Tohoku ($M_W = 9.0$)

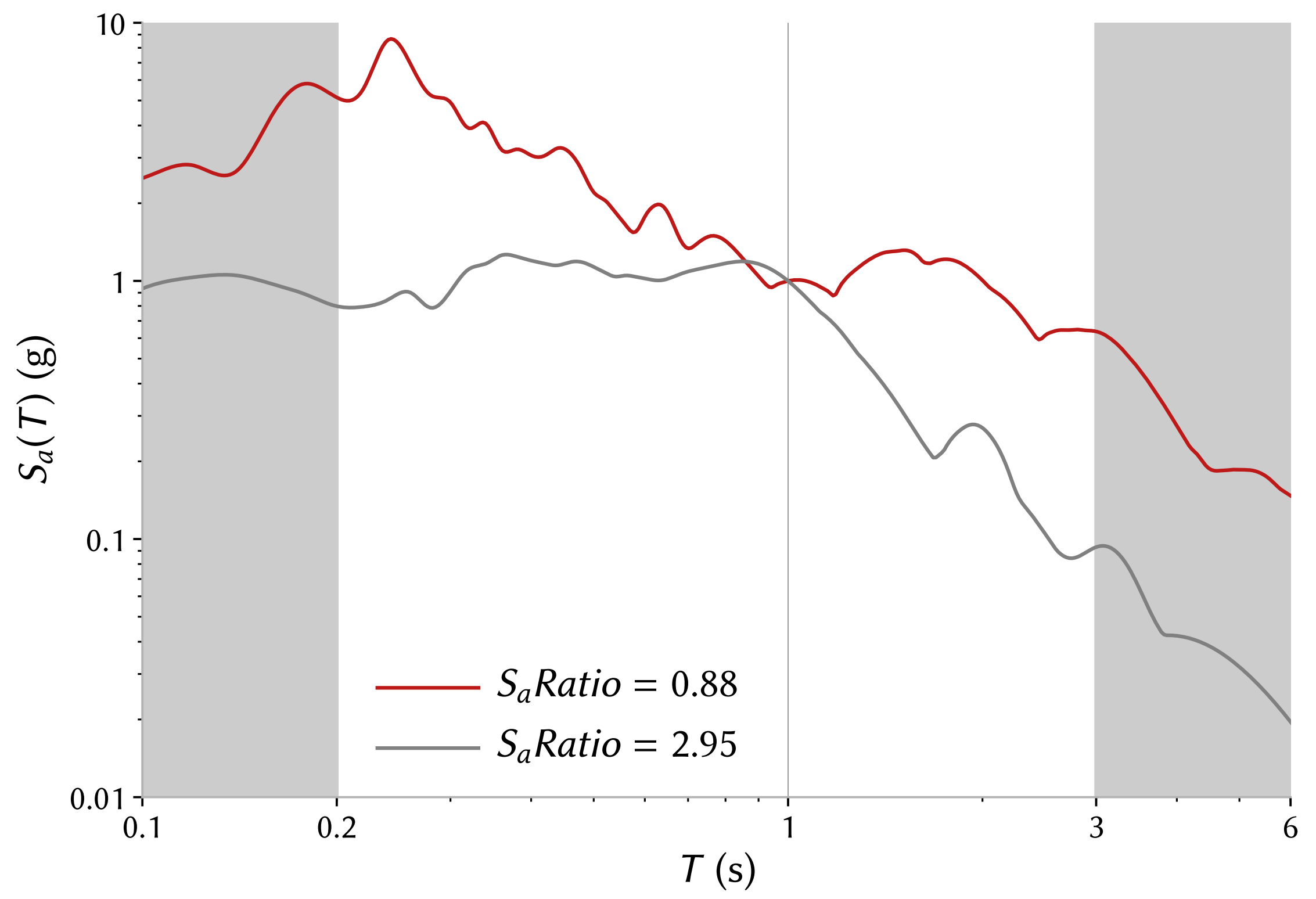


Short duration record from 1989 Loma Prieta ($M_W = 6.9$)



- Significant duration Ds was shown to be an effective metric of strong motion duration in a previous study by the authors

Examples of records with different spectral shapes

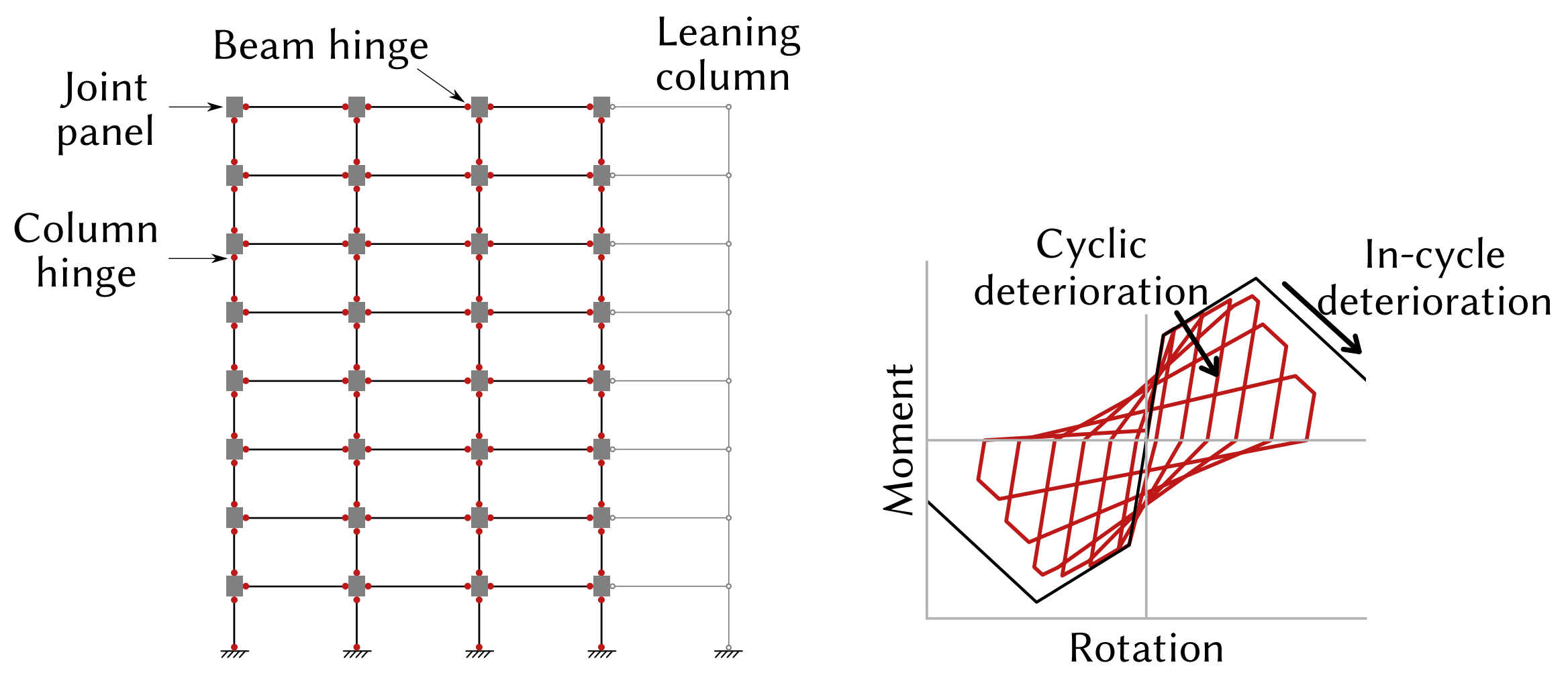


- S_aRatio is a dimensionless scalar metric of response spectral shape, similar to ε

$$S_aRatio(T, T_{start}, T_{end}) = \frac{S_a(T)}{S_{a,avg}(T_{start}, T_{end})}$$

Structural model

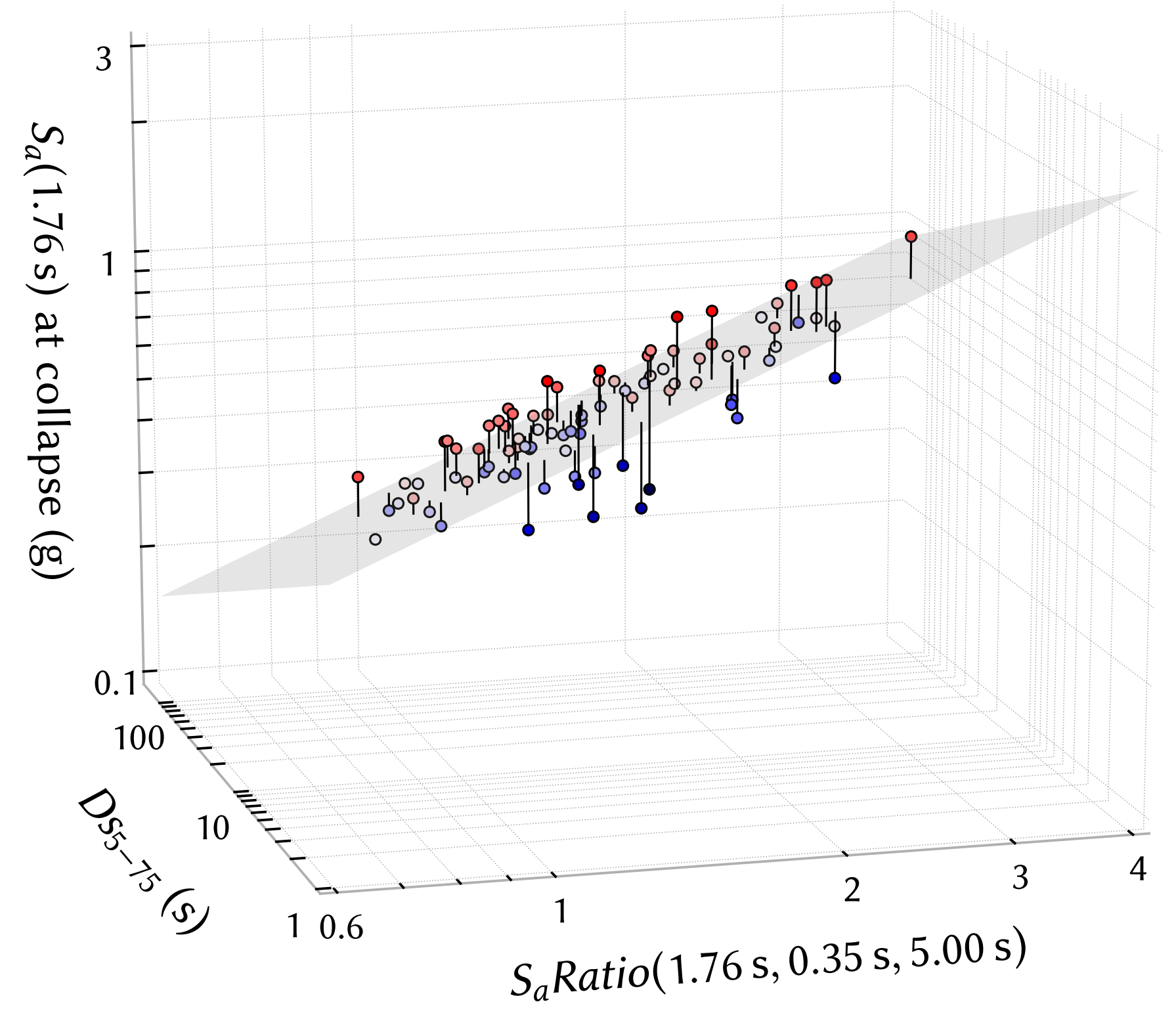
- Eight-story reinforced concrete moment frame building with a fundamental period 1.76 s, designed for a site in Seattle
- Model incorporates the strength and stiffness deterioration of structural components and destabilizing $P-\Delta$ effects: both characteristics required to capture the effect of duration



Hazard-consistent incremental dynamic analysis (H-IDA)

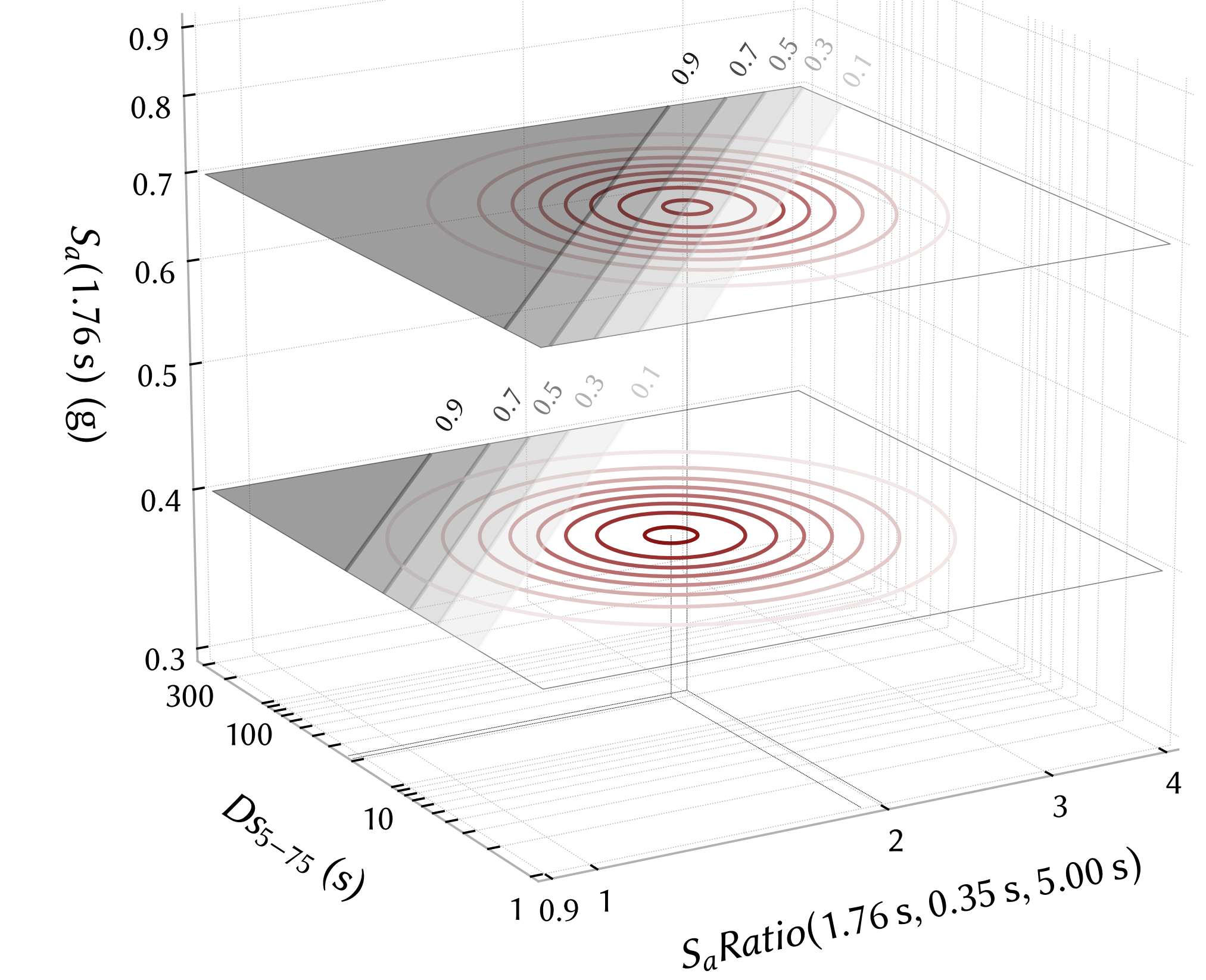
- Traditional incremental dynamic analysis (IDA) is conducted using a generic set of 88 records
- The following linear regression model is fit to the estimated ground motion collapse intensities

$$\ln S_a(T_1) \text{ at collapse} = c_0 + c_{dur} \ln Ds + c_{ss} \ln S_aRatio + \epsilon$$

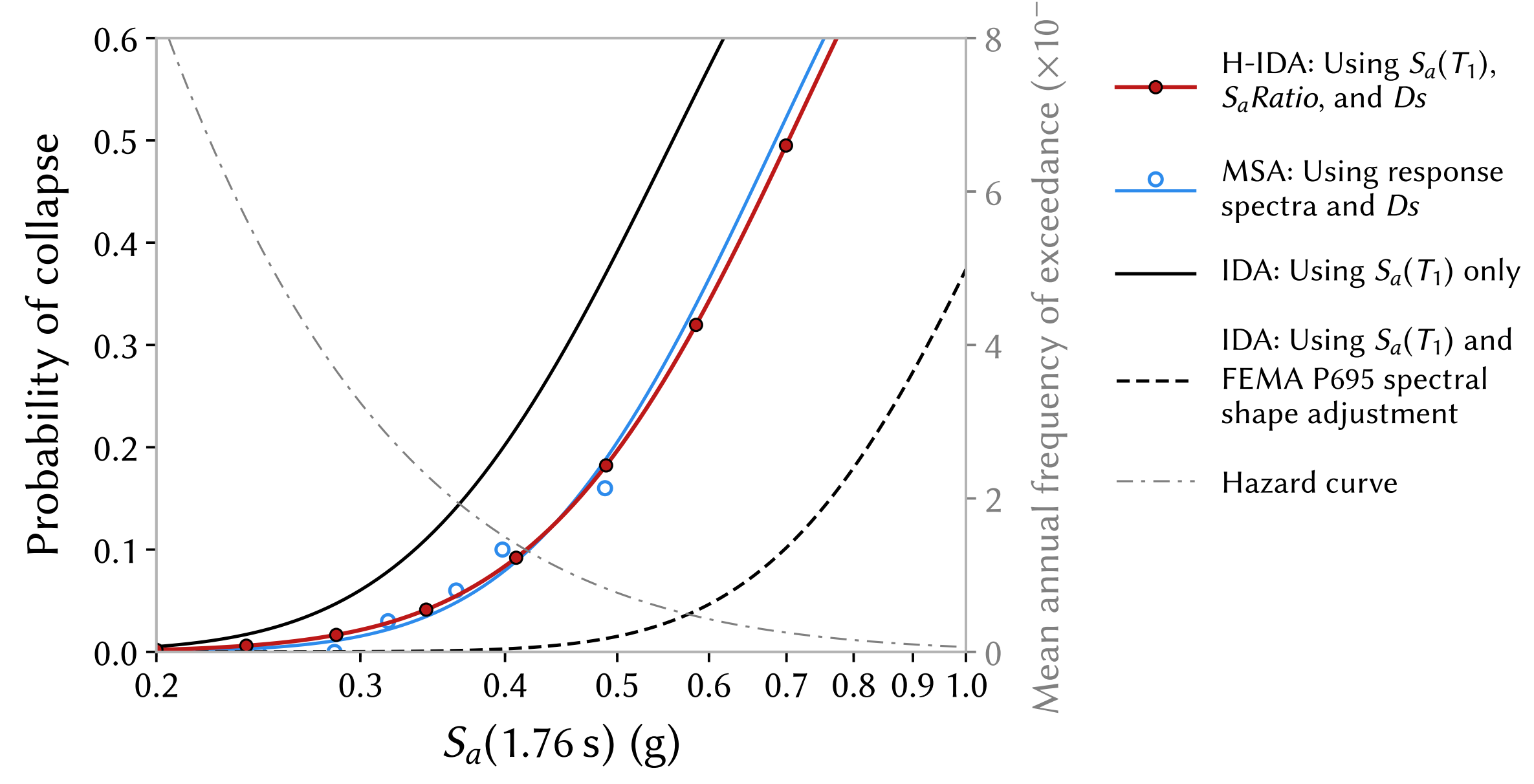


- R^2 is 0.81 using both Ds and S_aRatio as predictors, 0.40 using Ds alone, and 0.45 using S_aRatio alone
- Ground motions with long durations and low S_aRatio values cause collapse when scaled to lower intensity levels
- The regression coefficients c_{dur} and c_{ss} quantify the sensitivity of the structure to duration and spectral shape respectively
- The *failure surface* quantifies the probability a ground motion with a certain Ds and S_aRatio, when scaled to an intensity $S_a(T_1)$, will cause collapse: $P[\text{collapse} \mid \ln Ds, \ln S_aRatio, \ln S_a(T_1)]$
- The probability of collapse at an $S_a(T_1)$ level is computed by integrating site-specific conditional distributions of Ds and S_aRatio: $f[\ln Ds, \ln S_aRatio \mid \ln S_a(T_1)]$, over the failure domain

$$P[\text{collapse} \mid \ln S_a(T_1)] = \iint P[\text{collapse} \mid \ln Ds, \ln S_aRatio, \ln S_a(T_1)]\; f[\ln Ds, \ln S_aRatio \mid \ln S_a(T_1)]\; d(\ln Ds)\; d(\ln S_aRatio)$$



- Linear contours represent $P[\text{collapse} \mid \ln Ds, \ln S_aRatio, \ln S_a(T_1)]$, elliptical contours represent $f[\ln Ds, \ln S_aRatio \mid \ln S_a(T_1)]$, and the degree of overlap represents $P[\text{collapse} \mid \ln S_a(T_1)]$
- A hazard-consistent collapse fragility curve is computed by evaluating the reliability integral at different $S_a(T_1)$ levels



- The fragility curve computed using H-IDA agrees well with that computed using hazard-consistent multiple stripe analysis (MSA)

Design strength adjustment factors

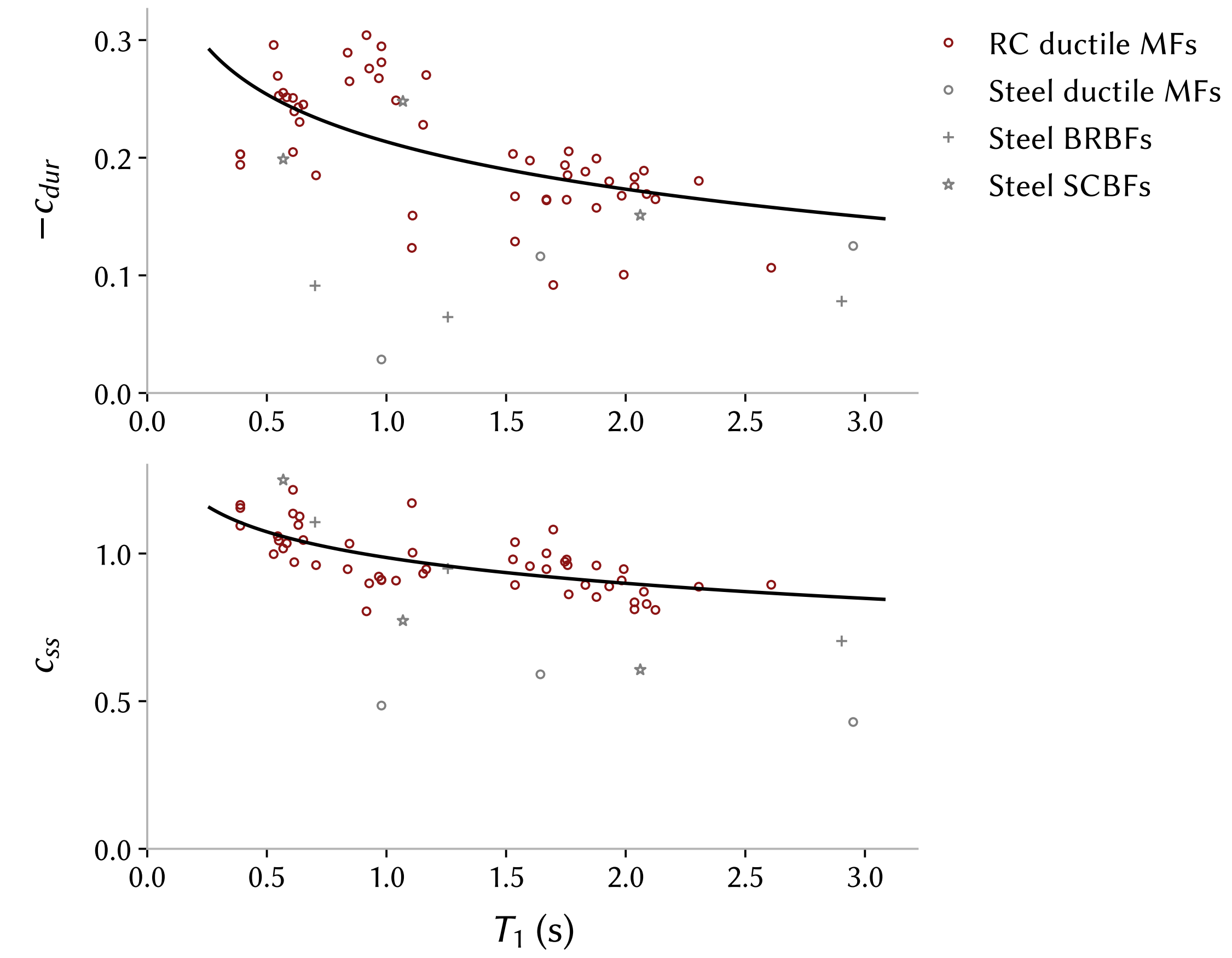
- A structure designed using the ELF procedure is assumed to possess an x % (usually 10 %) probability of collapse at the MCE_R level, under ground motions possessing a reference duration Ds^{ref} and spectral shape S_aRatio^{ref}
- Ds^{ref} and S_aRatio^{ref} are defined here as the median duration and spectral shape of the ground motions expected in Los Angeles
- If the structure is actually located at site where ground motions of duration Ds^{target} and spectral shape S_aRatio^{target} are expected, to maintain an x % collapse probability at the MCE_R level, it must be designed to a adjusted base shear

$$V = k'_{dur} k'_{ss} C_S W$$

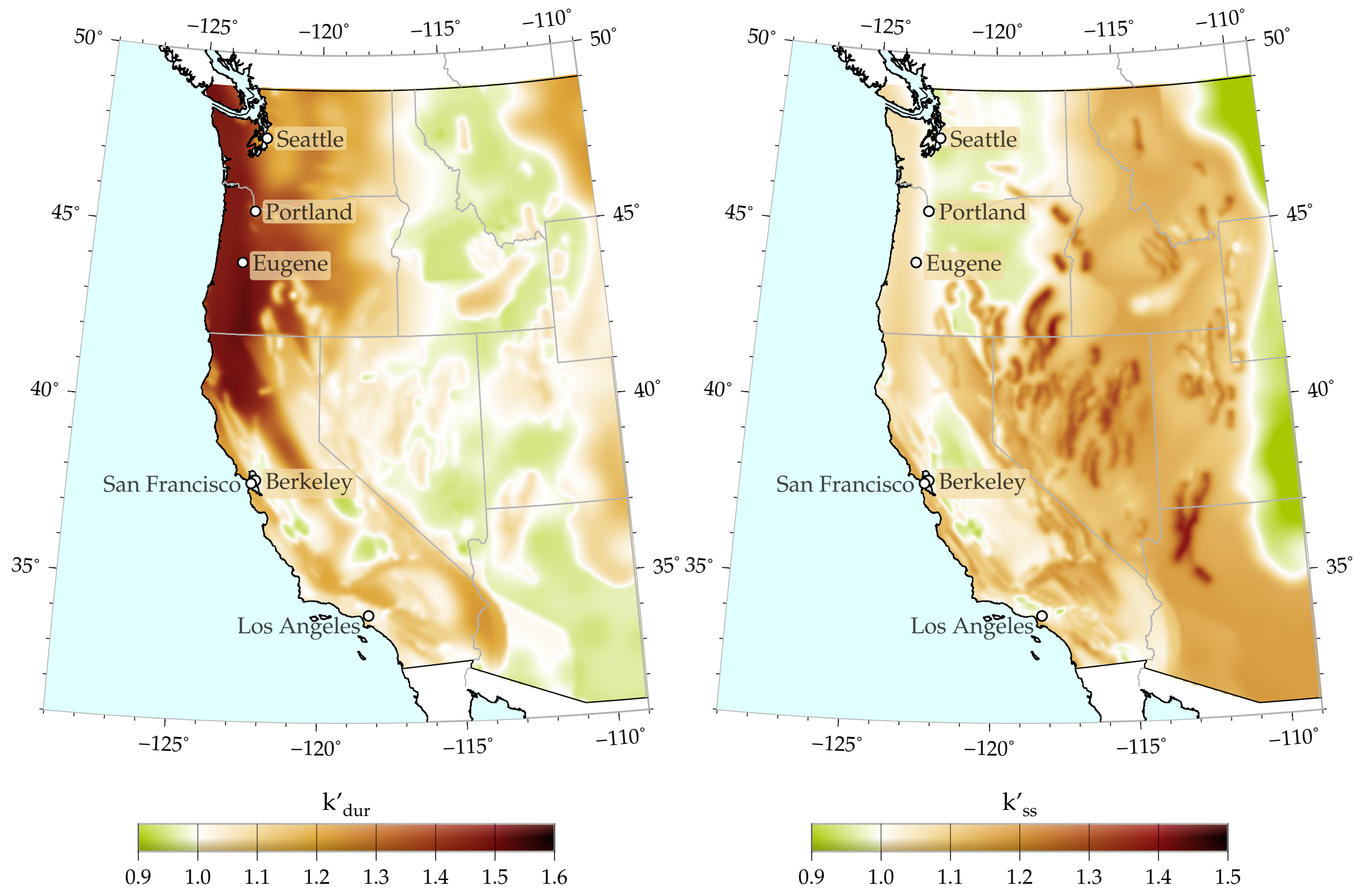
$$k'_{dur} = \left(\frac{Ds^{ref}}{Ds^{target}}\right)^{c_{dur}} \qquad k'_{ss} = \left(\frac{S_aRatio^{ref}}{S_aRatio^{target}}\right)^{c_{ss}}$$

- This method can be extended to nonlinear response history analysis (NLRHA) as well, by adjusting the MCE_R value instead

- c_{dur} and c_{ss} values are characterised for different structural systems by conducting similar analyses on a suite of models



- k'_{dur} and k'_{ss} values of 1 s reinforced concrete moment frames are computed for a number of different sites in Western USA



City	Ds_{5-75}^{target} (s)	k'_{dur}	S_aRatio^{target}	k'_{ss}	$k'_{dur}k'_{ss}$
Eugene	29.4	1.50	2.16	1.11	1.67
San Francisco	10.2	1.20	2.02	1.19	1.43
Portland	11.2	1.23	2.16	1.11	1.36
Seattle	9.6	1.18	2.20	1.09	1.29
Berkeley	4.9	1.03	2.38	1.01	1.04
Los Angeles	4.3	1.00	2.40	1.00	1.00

- Structures at sites located near the Cascadia subduction zone and along large crustal faults should be designed to higher base shears to maintain a geographically uniform risk of collapse

Conclusions

- Developed a hazard-consistent incremental dynamic analysis (H-IDA) procedure that can be used to compute a hazard-consistent collapse fragility curve by post-processing the results of IDA conducted using a generic record set
- Developed a framework to account for the effects of duration and spectral shape in the structural design, and thereby ensure a uniform risk of structural collapse over different geographical regions and structural systems