USER BULLETIN 9

FRAGILITY FUNCTION GENERATOR for Performance-Based Evaluation

This study has developed a spreadsheet using Visual Basics Application code for Excel to assist in the process of creating fragility functions. Fragility functions are mathematical equations used to calculate the probability of exceedance of any given limit state. They are used to define the performance of a structure to different loading conditions such as earthquake events. Fragility functions are commonly used to carry out performance-based analyses and determine the extent of damage the structure might undergo in future events such as earthquake, blast, tsunami, etc.

Before the application could be created, the entire process required to create fragility functions was performed using Wall 1.2 which was modelled previously. This was done to develop familiarity with the entire process to enable a full understanding of each step required to be programmed in the application. The steps performed were: ***(i)*** select a suite of ground motions, ***(ii)*** scale the selected suite of ground motions to have different intensities on the structure, ***(iii)*** perform nonlinear dynamic analyses using the ground motions, and ***(iv)*** calculate fragility functions.

1. Step I: Select a Suite of Ground Motions

Eleven ground motion time-history loads were used to account for the random nature of the earthquakes. The loading data was provided to VecTor2 (Wong et al., 2013) in acceleration-time pairs along the in-plane horizontal axis of the wall. The vertical component of the ground motion was not considered. The data was obtained from the PEER database. The earthquakes were selected based on the design response spectrum of the beforementioned wall. For this, the natural frequency of the wall was calculated using the force-displacement plot of the monotonic pushover analysis result.

The ground motions were selected to satisfy the following rule: the average of all the considered ground motions' spectral acceleration response matches or exceeds and does not fall below 90% of the risk-targeted maximum considered earthquake over the period range of 0.2 to 2 times the structure's highest natural period, T_0. This rule is required by modern codes for the seismic performance-based analysis of structures. Fig. 1 shows the design spectral acceleration response of the wall, the maximum considered spectral response (MCR), the 0.2 to 2 times period range, and the 90% target line for the ground motion selection.

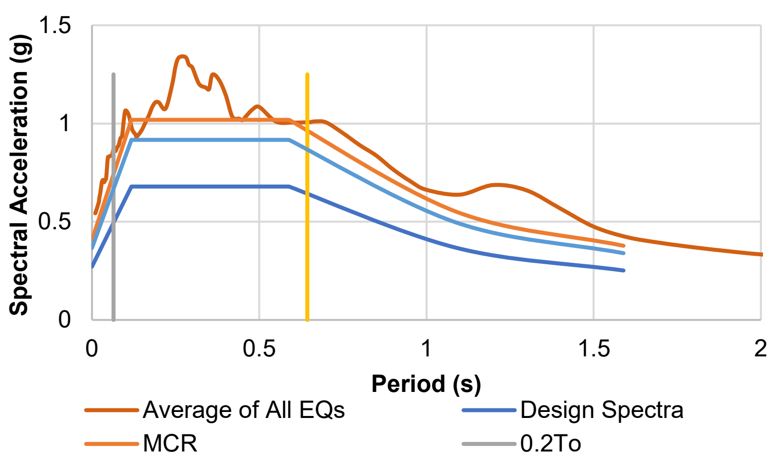

Fig. 1 Design response spectrum, MCER plot and the average design spectra of the considered earthquakes satisfying the given condition.

This document is prepared by Shivani Gandage (a third-year undergraduate student) as a part of a project supervised by Dr. Serhan Guner.

The ground motions from the PEER database were obtained by setting up the earthquake characteristics. The nature of the seismic fault was strike-slip with less than 50 km to the epicenter and Richter magnitude between 6 and 8. The earthquakes ground motions were scaled to satisfy the previously mentioned condition.

2. Step II: Scale the Selected Suit of Ground Motions to have Different Intensities on the Structure

Once the condition was met, a multiplying factor was calculated for each ground-motion selected in order to create records that imposed different seismic intensities on the wall. The structural results using different seismic intensities are required to obtain fragility functions. Thus, for each of the eleven ground motions selected, the multiplying factor was calculated to obtain peak ground accelerations of 0.3g, 0.5g, 0.7g, 0.9g, 1.1g, 1.3g, 1.5g, 2g, 2.5g, and 3g. This range was expected to yield wall responses from the initial elastic stages to the nonlinear stages.

$$Multiplying\ Factor = \frac{I}{S_a/F_{GM}}$$

where 'I' is the intensity required at the structural natural period (e.g., 0.3g, 0.6g, etc.); 'S_a' is the spectral acceleration that the scaled ground motion gives at the structure's natural period; and 'F_{GM}' is the factor used initially to scale the ground motion.

3. Step III: Perform Nonlinear Dynamic Analyses using the Ground Motions

The multiplying factors for each ground-motion were used to scale the ground-motion acceleration data, which was subsequently used as a load file (.EQR) in VecTor2. Other parameters for dynamic analysis were set in the VecTor.JOB file. For instance, the damping percentage, the number of load stages (based on the duration of the earthquake and increment factor) and the repetitions after which the output files are generated (which depends on the time step and should not exceed one-tenth of the structure's natural period) are specified in the VecTor.JOB file.

One analysis was run for each of the 11 selected ground motions and each of the 10 considered intensities, which resulted in 110 different analyses performed. The postprocessor Janus was used to obtain the results, which are presented in the form of the maximum displacement of the topmost node of the wall in Fig. 2.

Record sequence no.	Intensities									
	0.3	0.5	0.7	0.9	1.1	1.3	1.5	2	2.5	3
879	2.286	4.108	5.91	8.223	10.298	12.562	14.836	22.377	29.475	38.834
864	1.589	2.15	2.889	3.776	4.862	6.27	7.747	12.045	16.64	21.542
183	2.286	3.783	5.419	7.241	8.809	10.213	11.114	15.754	22.783	32.753
451	1.558	1.974	2.547	3.476	4.84	6.296	7.434	10.996	15.268	19.701
727	2.325	3.699	5.311	8	10.53	12.376	13.907	19.844	27.576	36.348
848	1.629	2.49	3.253	4.061	4.938	5.926	6.881	9.943	13.414	16.628
900	2.474	3.958	5.859	7.659	9.869	12.338	14.995	22.038	31.198	44.529
1120	1.429	2.295	3.329	4.603	6.391	7.793	9.383	13.804	19.126	26.658
20	2.236	2.984	3.722	4.685	6.122	7.605	9.443	14.039	19.552	26.422
180	1.549	2.862	4.598	6.602	8.753	11.104	13.369	19.22	27.265	35.446
181	1.48	2.145	2.708	3.724	4.674	5.191	6.336	9.125	12.629	16.578

Fig. 2 The results from the dynamic analysis of Wall 1.2 with intensities in 'g' units.

4. Step IV: Calculate Fragility Functions

After running the simulations and obtaining the maximum displacement at the top of the wall for each ground motion record, the first step was to calculate fragility functions, which require the definition of the limits states that characterize the state/performance of the structure. These limit states are defined in terms of an engineering demand parameter (i.e., a form of measure of the structure's response). In this study, the wall drift was used. The corresponding EDP (drift) values are *0.599%, 0.831%, and 1.358%*, respectively, and define a state of low, moderate, and extensive damage of the wall. These thresholds were obtained from the monotonic pushover curve of Wall 1.2.

Finally, the formula below was utilized to calculate the fragility function. The obtained plot is presented in Fig. 3. In order to develop fragility functions with higher levels of accuracy for practical applications, it is recommended to consider a larger number of ground motions (i.e., significantly more than the 11 ground motions considered in this study). This results in the development of reliable fragility functions and consequently high-accuracy seismic performance and vulnerability assessments.

$$P(x \geq D) = 1 - 0.5\left[1 + Erf\left(\frac{\ln\left(\frac{D}{\mu}\right)}{\sqrt{2} * \beta}\right)\right]$$

Where, $P(x \geq D)$ represents the probability of exceedance of a given limit state 'D' i.e., the threshold in terms of the EDP defined; Erf is the Gaussian error function; 'β' is the standard deviation of the natural logarithm of the data points; 'μ' is the median of the EDP at the given ground motion, calculated by the exponential regression of the user entered data.

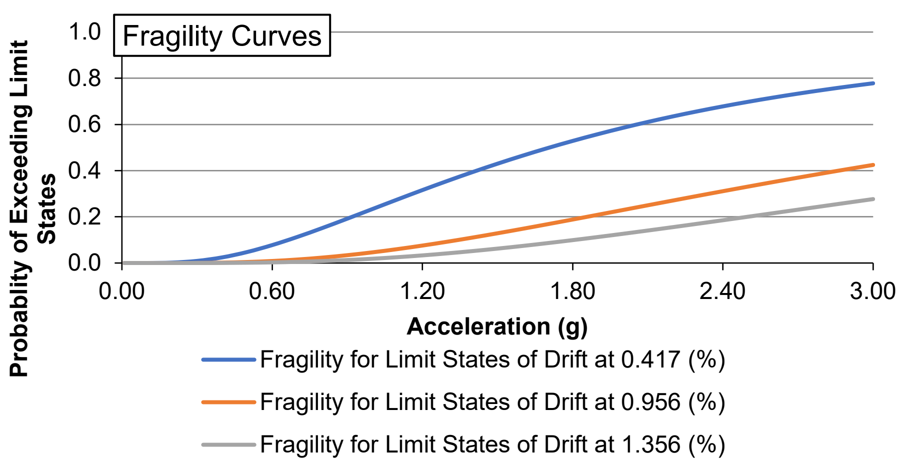

Fig. 3 Fragility plot for Wall 1.2 from 11 strong ground motion records and 10 intensities per record.

The fragility curves calculated and shown in Fig. 3 permit a quick visual assessment of the performance of the tested CLT wall. For instance, it is possible to see that at an earthquake intensity of 3.0g, there is an 80% probability that the CLT wall will exceed the limit state of drift 0.417% (i.e., low damage) and only a 25% probability that the CLT wall will exceed the limit state of drift 1.356% (i.e., extensive damage). Thus, considering that it is quite rare for earthquakes to produce an excitation of 3.0g, the fragility function permits several conclusions, one of which is that the wall has good probabilities of staying below the moderate and extensive limit states for usual earthquake intensities.

5. Spreadsheet

The spreadsheet is called 'Fragility Function Generator' and generates fragility plots based on the user entered data. The inputs required from the user are the pairs of load intensity (i.e., in this study, the peak ground accelerations discussed in Section 2) and the corresponding structure's response (i.e., in this study, the wall drifts). Both the load intensity and the corresponding structure response can be of any unit type that the user defines. The user must then define the number of performance limits to consider and their corresponding values. The spreadsheet uses the Gaussian error function, a univariate regression model to fit a power curve, and assumes a two-parameter log-normal distribution to calculate the fragility functions (i.e., the spreadsheet uses the equation shown in Section 4). The result is a plot containing one fragility function for each performance limit defined (see an output example in Fig. 3). These can be used to assess the vulnerabilities of various structures including buildings, bridges, etc., or structural components. Also, damage-levels can be estimated for a given load intensity considered (i.e., peak ground acceleration in this study). Available from: https://www.utoledo.edu/engineering/faculty/serhan-guner/spreadsheets.html

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Citation Information

Please use the following references when citing Fragility Function Generator spreadsheet in a publication.

Gandage, S., Salgado, R., and Guner, S. (2019) "FFG: Fragility Function Generator," Macro-Enabled Excel Spreadsheet, Department of Civil and Environmental Engineering, The University of Toledo, Ohio, USA. https://www.utoledo.edu/engineering/faculty/serhan-guner/spreadsheets.html
https://youtu.be/Rah5detuekU

Gandage, S., Salgado, R., and Guner, S. (2022) "User Bulletin 9: Fragility Function Generator for Performance-Based Evaluation," Documentation, 4 pp.
https://www.utoledo.edu/engineering/faculty/serhan-guner/docs/B9_FragilityFunctionGenerator.pdf

Related Publication

The following publication uses fragility functions in the context of performance-based earthquake engineering, which you may find useful.

Salgado, R. and Guner S. (2018) "A Comparative Study on Nonlinear Models for Performance-Based Earthquake Engineering," Engineering Structures, 172, 382-391.
http://www.utoledo.edu/engineering/faculty/serhan-guner/docs/JP9_Salgado_Guner_2018.pdf

References

Wong P.S., Vecchio F.J. and Trommels H. (2013) "VecTor2 and Formworks User's Manual," Technical Report, Department of Civil Engineering, University of Toronto, ON, Canada, 347 pp. Retrieved from http://vectoranalysisgroup.com/software.html