Issues in Dependency Modeling in Multi-Unit Seismic PRA

Taotao Zhou

Mohammad Modarres

Enrique López Droguett

Center for Risk and Reliability

University of Maryland, College Park

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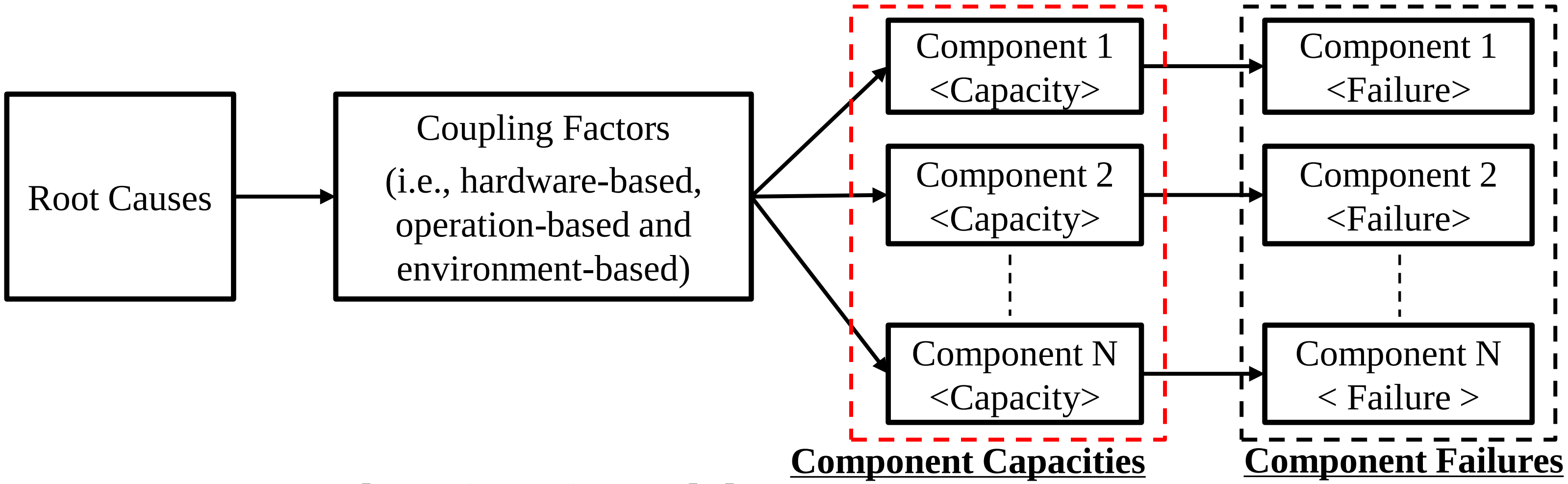
Presentation Overview

- Background and Motivation
- State-of-the-Art on Seismic Dependency Modeling
- Existing Issues with Demonstration
- Conclusions

Background and Motivation



- **Common Cause Failure (CCF) Models:**
  - Shock Model and Non-Shock Model.
- **Recent efforts to enhance the current CCF models:**
  - Improve the quality of CCF database.
  - Formulate a casual CCF model to link relevant sources with Bayesian network.
  - Address other limitations, such as improve uncertainty treatment.
  - Establish a multi-unit PRA considering dependencies across reactor units, e.g., external events, especially **seismic event**.

State-of-the-Art

- Current Approaches to Seismic Dependency Modeling:

1) Follow the traditional parametric CCF methods in the internal events PRAs.

2) Incorporate the dependencies by means of the correlation between seismic failures. (i.e., Seismic Safety Margins Research Program (SSMRP); Mike Bohn's thumb rules).

3) Incorporate the dependencies by means of correlation of the ground acceleration capacity.

→ Proposed by Reed et al., 1985, referred to as Reed-McCann method

- J.W. REED, M.W. MCCANN, JR.J. IIHARA, and H.H. TAMJED. "Analytical Techniques for Performing Probabilistic Seismic Risk Assessment of Nuclear Power Plants," Proc. of the 4th International Conference on Structural safety and reliability, Kobe, Japan, May 27-29 (1985).
- R. J. BUDNITZ, G. S. HARDY, D. L. MOORE and M. K. RAVINDRA. "Correlation of Seismic Performance in Similar SSCs (Structures, Systems, and Components)," Final Report Draft, Lawrence Berkeley National Laboratory, Berkeley, California (2015) (under NRC review)

4) Combined methodologies to exploit the features of three approaches above.

→ Derive the CCF parameter given the correlation coefficient.

- J. U. KLUGEL. "On the treatment of dependency of seismically induced component failures in seismic PRA," *Transactions of the 20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)*, Helsinki, Finland, August 9-14 (2009).
- M. PELLISSETTI and U. KLAPP. "Integration of correlation models for seismic failures into fault tree based seismic PSA," *Transactions of the 21st International Conference on Structural Mechanics in Reactor Technology (SMiRT 21)*, New Delhi, India, Nov 6-11 (2011).

State-of-the-Art (cont.)

- Issues and Challenges:
  - Features of dependencies might be altered with different interpretations of seismic hazard, fragility development and reactor design research results.
  - Given the features of dependencies available, there are issues in the current methods to quantity joint fragility:

    (1) Inappropriate equivalence assumption between β-factor and correlation coefficient;

    (2) Issues in the numerical quantification procedure in the Reed-McCann method.

Hypothesis between β-Factor and Correlation Coefficient

- An analytical example:
  - A parallel system composed of two components A and B.
  - The component states: X_A, X_B; system state: X_{AB}.
  - The marginal failure probability P_A, P_B; joint failure probability P_{AB}.
- Correlation coefficient ρ_{AB} :

$$\rho_{AB} = \frac{\mathrm{cov}[X_A, X_B]}{\sigma_{X_A} \cdot \sigma_{X_B}} = \frac{E[X_{AB}] - E[X_A] \cdot E[X_B]}{\sigma_{X_A} \cdot \sigma_{X_B}} = \frac{P_{AB} - P_A P_B}{\sqrt{P_A(1 - P_A)P_B(1 - P_B)}}$$

- Rules (given equivalence assumption works):
  - Correlation coefficient is less than the actual β-factor.

$\rho_{AB} < \beta$ lead to non-conservative estimate

  - Correlation coefficient is no less than the actual β-factor.

$\rho_{AB} \geq \beta$ lead to conservative estimate

Hypothesis between β-Factor and Correlation Coefficient (cont.)

- The joint failure probability $\mathrm{P_{AB}}$ can be expressed as (assume $\mathrm{P_A} = \mathrm{P}_B = P$):

1) $\mathrm{P_{AB}}=\mathrm{P_A P_B}+\rho_{\mathrm{AB}}\sqrt{\mathrm{P_A}(1-\mathrm{P_A})\mathrm{P_B}(1-\mathrm{P_B})} = \mathrm{P}^2+\rho_{\mathrm{AB}}\cdot \mathrm{P}\cdot(1-\mathrm{P})$

2) $\mathrm{P_{AB}} = (1-\beta)^2\mathrm{P}^2 + \beta\cdot \mathrm{P}$

- Equating equations (1) and (2) to find the analytical relationship between ρ_{AB} and β-factor:

$$\mathrm{P}\cdot\beta^2 + (1-2\mathrm{P})\cdot\beta - \rho_{\mathrm{AB}}\cdot(1-\mathrm{P}) = 0$$

- The analytical solution provides the actual relationship between the β-factor and ρ_{AB} as:

$$\beta = \frac{(2\mathrm{P}-1)+\sqrt{(1-2\mathrm{P})^2+4\mathrm{P}\cdot(1-\mathrm{P})\cdot\rho_{\mathrm{AB}}}}{2\mathrm{P}}$$

Hypothesis between β-Factor and Correlation Coefficient (cont.)

- Let's assume $\beta < \rho_{AB}$ (<u>ensure conservative estimate</u>), then:

$$\begin{cases} 0 < \frac{(2P-1)+\sqrt{(1-2P)^2+4P\cdot(1-P)\cdot\rho_{AB}}}{2P} < \rho_{AB} \\ 0 < \rho_{AB} \le 1 \\ 0 < P \le 1 \end{cases} \rightarrow \text{Null solution}$$

- Let's assume $\beta \ge \rho_{AB}$ (<u>cause non-conservative estimate</u>), then:

$$\begin{cases} \rho_{AB} \le \frac{(2P-1)+\sqrt{(1-2P)^2+4P\cdot(1-P)\cdot\rho_{AB}}}{2P} \le 1 \\ 0 < \rho_{AB} \le 1 \\ 0 < P \le 1 \end{cases} \rightarrow \begin{cases} 0 < P \le 1 \\ 0 < \rho_{AB} \le 1 \end{cases}$$

Limitation of Reed-McCann Method

Case No.	Dependency	System Configuration	Description
1	Dependent Components	Intersection of components (3/3)	All three dependent components fail
2		Union of components (1/3)	At least one dependent component fails
3	Independent Components	Intersection of components (3/3)	All three independent components fail
4		Union of components (1/3)	At least one independent component fails

- Use the example problem from Reed et al. for examination purpose.
- Examine the performance by comparing the joint fragilities of four different cases.
- Lack of sufficient benchmarking results (two sets of results exist).
  1) Reed et al. presented results for all the four cases, but only for one specific sample set within the ten sample sets generated in total.
  2) Budnitz et al. presented results for two dependent cases (i.e., case 1 and case 2) using the same sample set in Reed et al. Results are also provided for ten equally weighted sample sets, while based on one iteration.

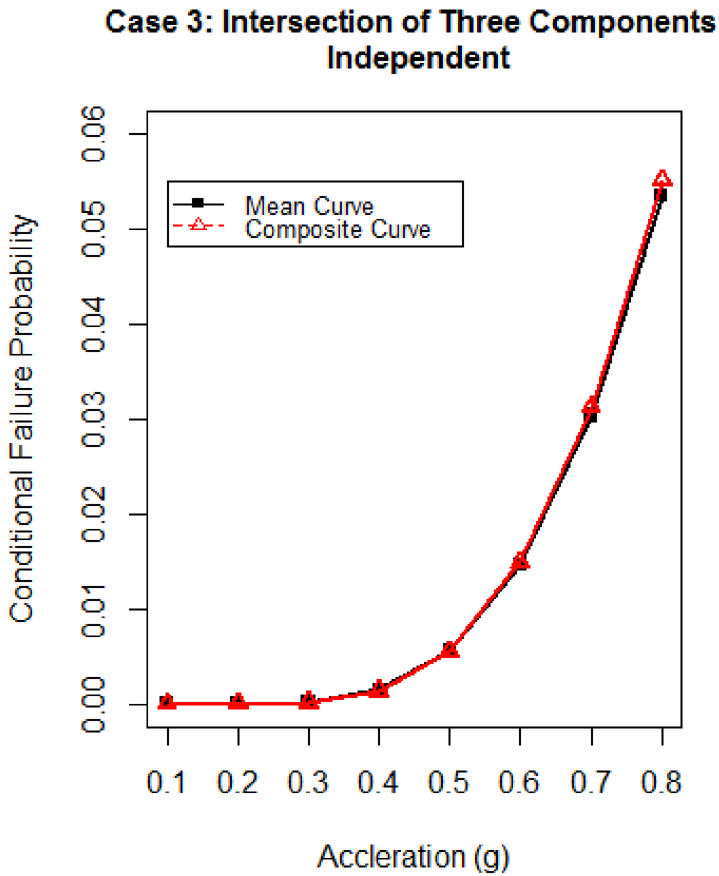
- J.W. REED, M.W. MCCANN, JR.J. IIHARA, and H.H. TAMJED. “Analytical Techniques for Performing Probabilistic Seismic Risk Assessment of Nuclear Power Plants,” Proc. of the 4th International Conference on Structural safety and reliability, Kobe, Japan, May 27-29 (1985).
- R. J. BUDNITZ, G. S. HARDY, D. L. MOORE and M. K. RAVINDRA. “Correlation of Seismic Performance in Similar SSCs (Structures, Systems, and Components),” Final Report Draft, Lawrence Berkeley National Laboratory, Berkeley, California (2015) (under NRC review)

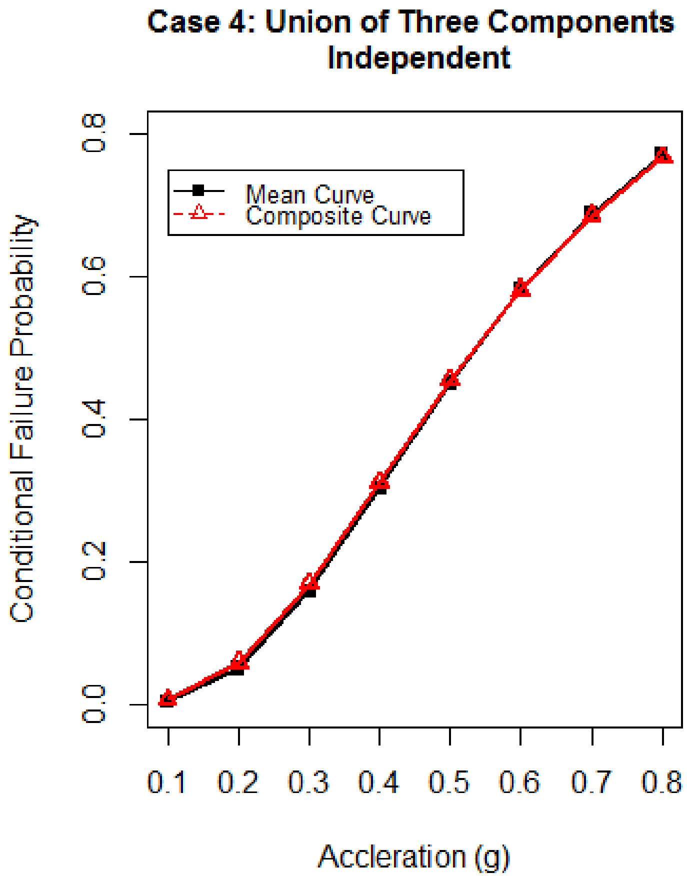
Limitation of Reed-McCann Method (cont.)

- **Comparison Study:**
  - Comparison between the composite fragility curve and mean fragility curve in the independent cases (i.e., case 3; case 4);
  - Comparison Between dependent and independent cases (i.e., case 1vs. case 3; case 2 vs. case 4).
- **Rules:**
  1) Composite fragility curve is equivalent to mean fragility curve.
  2) The correlation for the intersection cases always increases the tendency of joint failure. $\frac{y_1}{y_3} > 1$
  3) The correlation for the union cases always reduce the likelihood of joint failure. $\frac{y_4}{y_2} > 1$
- **Performance index α:**

$$\alpha = \frac{\sum_{i=1}^{N}\left[I\left(\frac{y_1^i}{y_3^i}\right) \cdot I\left(\frac{y_4^i}{y_2^i}\right)\right]}{N} \;;\; i = 1, \dots, N$$

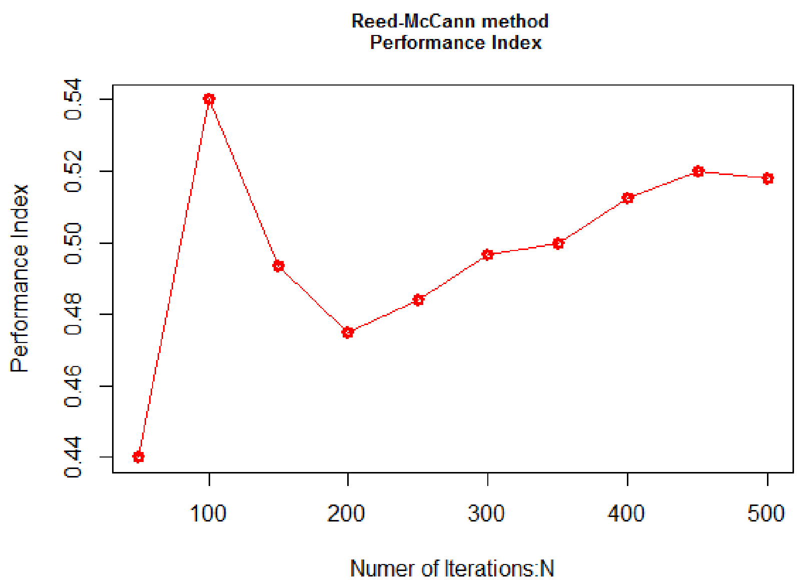
Comparison – Independent Cases



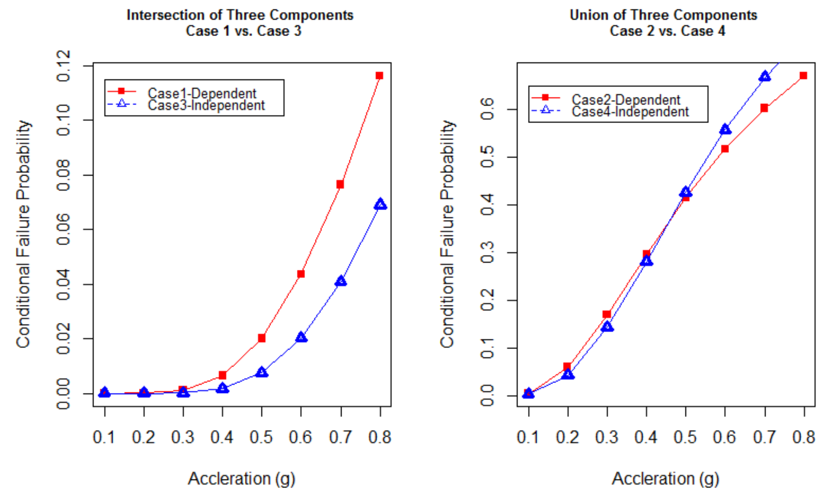


Comparison – Dependent and Independent Cases

Performance index given ten different numbers of iterations N



Example results – Intersection & Union (seed number = 500)



Conclusions

- The equivalence hypothesis between the β-factor and correlation coefficient is not appropriate.
- The Reed-McCann method is not performing well to characterize the contribution of dependencies.
- There is a need to develop an improved method for characterizing the SSCs with shared features

Thank You!