Comparison of various methods to quantify a fault tree for Seismic PSA

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1. Introduction

Typically, quantification (evaluation of frequency) of a sequence in a PSA is performed by generating minimal cut sets and quantifying it using REA (Rare event approximation) or MCUB (Minimal cut upper bound) method.

MCUB gives more exact value than REA. But, it is known that REA and MCUB method may produce very conservative value when a probability of each event is larger than 0.1 such as in seismic PSA [1].

The PSA software AIMS-PSA [2] and FTREX [3] developed in KAERI use REA and MCUB method to quantify a PSA model. Thus, it is necessary to verify the quantification result for seismic PSA. There are several method/software available for the verification. ACUBE [4] developed by EPRI quantifies the pre-generated minimal cut sets using BDD (binary decision diagram) method. FTeMC [5] developed by KAERI is based on Monte Carlo method. FtBdd [6] developed by KAERI is based on BDD, but it can be applied for small fault trees.

In section 2, a simple example is provided to characterize various methods. In section 3, the results of those methods are compared for a seismic PSA model.

2. Quantification for a Simple Model

We have tested various methods for a simple model that has events whose probability is larger than 0.1. Two models are used. Case 1 is corresponding to a core damage model of Level-1 PSA. Case 2 represents a PDS (plant damage state) model of Level-2 PSA, which is the extension of Case 1 model.

2.1 Sample Case 1(Simple ET/FT Model)

The event tree for Case 1 is given in Fig. 1.

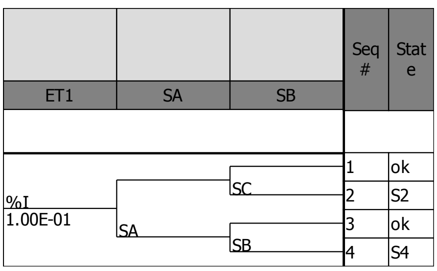

Fig.1. Event tree for Case 1

Fault trees for branches of the event tree are given in Fig. 2, which includes events whose probabilities are larger than 0.1.

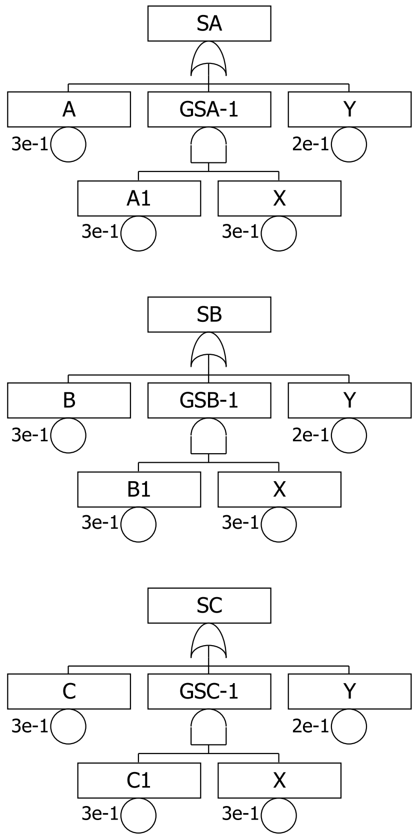

Fig.2. Fault trees for Case 1

The quantification results from various methods are given in Table 1. MCS in Base means that the quantification is performed using minimal cut sets generated. PI in Base means that the quantification is done using prime implicants.

The prime implicants generated by BDD method can give the exact value. The results of FtBdd are the exact values.

Let me summarize the results of Table 1:

- BDD method produces exact values.
- REA, MCUB and ACUBE for minimal cut sets produce the conservative values. They produce very conservative values especially for the sequence S2. The reason is that the 'Delete term approximation' is used to generate minimal cut sets, which is an approximate result [1].
- MCUB for prime implicants underestimates the value because it include negate.

2.2 Sample Case 2 (Extended Model corresponding to PDS Event Tree)

The event tree of Case 1 is extended to describe a PDS event tree, which is shown in Fig. 3.

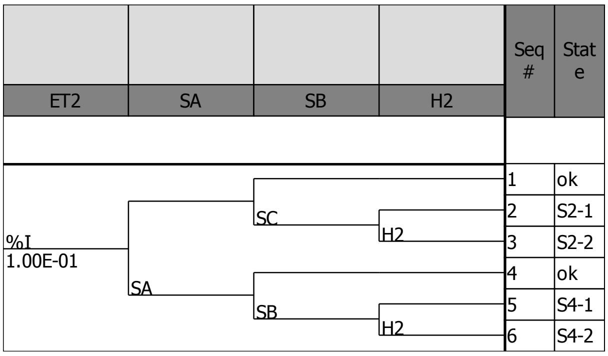

Fig.3. Event tree for Case 2

The fault tree for branch H2 is given in Fig. 4. The fault trees for SA, SB and SC are the same as Case 1.

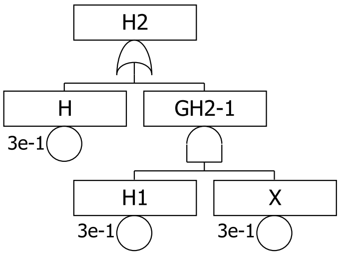

Fig.4. Fault tree for Case 2

The quantification results are given in Table 2. It gives an idea for a PDS event tree:

- If the quantification is performed using minimal cut sets, the error for Case 2 becomes larger than Case 1. Note that the sequence S2 of Case 1 is divided into sequences S2-1 and S2-2 of Case 2. But, the value for S2 is not divided into S2-1 and S2-2.
- It means that error becomes larger when the core damage model is extended to the plant damage state model.

3. Quantification for a Seismic PSA Model

A large difference is found between quantification values for both core damage model and plant damage state model in a seismic PSA, because of reasons discussed in Section 2.

It is necessary to estimate the frequency of each sequence more exactly. BDD can provide the exact value, but it cannot be used for large fault tree such as a PSA of a nuclear power plant.

In this paper, FTeMC is used to evaluate the frequency of each sequence. FTeMC is a software to calculate the value for a fault tree using Monte Carlo method. FTeMC cannot handle the post processing recovery rule which is not expressed in the form of fault tree. No large difference is found between values after recovery and before recovery for the seismic PSA model. It is fortunate enough to evaluate values without considering recovery.

The quantification results for the seismic PSA are given in Table 3, where the ratio to the value of FTeMC is given.

REA and MCUB (sum of sequences) values, which are calculated by summing values for all sequences, are 3.9 and 9.6 times larger than that of FTeMC, respectively. ACUBE (whole) and MCUB (whole) values for whole model are 3% and 20% larger than that of FTeMC, which results in smaller error than MCUB (sum of sequences). If we quantify each sequence, it is expected that the error becomes larger.

5. Conclusions

REA and MCUB may produce very conservative value for a seismic PSA model which includes events whose probabilities are large. Every method/software used in quantification of a PSA model has limitation. This paper compares various methods for PSA quantification. The characteristics of various quantification methods are summarized in Table 4.

It is not easy to get the exact value for every case. We should recognize the limitation of each method/software when analyzing the quantification results for PSA. To verify the results, a supporting analysis can be used using other software such as Monte Carlo method.

REFERENCES

[1] S. Epstein, A. Rauzy, Can we trust PRA?, Reliability Engineering and System Safety 88,195–205, 2005

[2 Sang Hoon Han, et al., Improved Features in a PSA Software AIMS-PSA, Korean Nuclear Society Spring Meeting, Pyeongchang, Korea, 2010

[3] W.S. Jung, ZBDD Algorithm Features for an Efficient Probabilistic Safety Assessment, Nuclear Engineering and Design, Vol.239, pp.2085-2092, 2009

[4] ABUBE 2.0 software Manual 3002003169, EPRI, 2014

[5] Sang Hoon HAN and Ho-Gon LIM, Top event probability evaluation of a fault tree having circular logics by using Monte Carlo method, Nuclear Engineering and Design 243, 336– 340, 2012

[6] Fault Tree Analysis using BDD (FtBdd), KAERI-ISA-MEMO-2009-BDD-01, KAERI, 2009

Table 1. Quantification results for Case 1.

Base	Method	S2 (3)	S4 (3)	Whole (4)	Remark
MCS (1)	REA	3.900E-02	3.710E-02	7.610E-02	
	MCUB	3.630E-02	3.294E-02	5.728E-02	Sum=6.924E-02 (5)
	Acube (BDD)	3.630E-02	3.128E-02	5.563E-02	Sum=6.758e-2
PI (2)	FtBdd (BDD)	1.776E-02	3.128E-02	4.904E-02	Exact Solution (6)
	Acube (BDD)	1.776E-02	3.128E-02	4.904E-02	
	MCUB	1.698E-02	3.128E-02	4.826E-02	Underestimate (7)

1) MCS : Quantification is done for minimal cut sets
2) PI : Quantification is done for prime implicants obtained using BDD
3) Quantification is done for each sequence
4) Quantification is done for whole model
5) The value is the sum of S2 and S4. Note that it is larger than the value of Whole for MCS.
6) The results are the exact solution calculated by using BDD.
7) MCUB may underestimate the value for a model that has negate

Table 2. Quantification results for Case 2.

Base	Method	S2-1	S2-2	S4-1	S4-2	Whole	Remark
MCS	REA	3.900E-02(1)	1.710E-02(1)	3.710E-02	1.617E-02	1.094E-01	
	MCUB	3.630E-02(1)	1.617E-02(1)	3.294E-02	1.515E-02	6.962E-02	Sum=1.006e-1(3)
	Acube (BDD)	3.630E-02(1)	1.410E-02(1)	3.128E-02	1.196E-02	5.563E-02	Sum=9.364e-2(3)
PI	FtBdd (BDD)	1.117E-02(2)	6.587E-03(2)	1.933E-02	1.196E-02	4.904E-02	Exact Solution
	Acube (BDD)	1.117E-02	6.587E-03	1.933E-02	1.196E-02	4.904E-02	
	MCUB	1.091E-02	6.446E-03	1.810E-02	1.147E-02	3.327E-01	Underestimate

1) The sequence S2 in Case 1 is divided into sequences S2-1 and S2-2 in Case 2. The sum of S2-1 and S2-2 are larger than the value of S2.
2) In theoretically, the sum of S2-1 and S2-2 should be the same as the value of S2.
3) The value is much larger than that of Case 1

Table 3. Quantification result for Seismic PSA Model

Base	Method	0.3g(1)	0.5g	0.7g	0.9g	1.1g	Total(5)
Fault Tree	FTeMC (10^5 sampling)	1.00	1.00	1.00	1.00	1.00	1.00
MCS	MCUB (Sum of sequences)	1.06(2, 3)	1.26	2.70	5.83	8.31	3.88
	MCUB (Whole)	1.05(4)	1.08	1.40	1.08	1.01	1.20
	REA	1.07	1.46	4.16	14.17	32.70	9.64
	ACUBE (Whole)	1.03(4)	1.05	1.04	1.01	1.00	1.03

1) The seismic PSA are performed for 5 seismic groups such as 0.3g, 0.5, 0.7g, 0.9g and 1.1g.
2) The ratio of MCUB to FTeMC
3) Calculated by summing values for all sequences
4) Calculated for whole PSA model
5) Sum of values for 5 seismic group

Table 4. Characteristics of quantification methods

Method		Characteristics
MCS		- Generate minimal cut sets (from which several analyses can be done such as importance analysis) - Post processing recovery analysis possible - Minimal cut sets itself is the approximation.
	REA[(1)]	- Produce very conservative value - Should be verified
	MCUB[(1)]	- Produce reasonable value for whole event tree - Produce conservative value for each sequence - May underestimate if the model includes negate - Should be verified
	BDD (ACUBE) [(1)]	- More exact than MCUB - Produce reasonable value for whole event tree - Produce conservative value for each sequence - Should be verified
BDD		- Generate prime implicant / minimal cut sets - Can produce exact value for each sequence for small fault trees - Cannot be used for PSA model
Monte Carlo (FTeMC)		- Does not generate minimal cut sets - Can calculate near exact value for each sequence - Cannot handle post processing recovery analysis

1) Quantification is performed for minimal cut sets generated