Approximate Formulas for the Estimation of Common Cause Failure Probabilities of Components under Mixed Testing Strategies

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1. Introduction

For the case where trains or channels of standby safety systems consisting of more than two redundant components are tested in a staggered manner, the standby safety components within a train can be tested simultaneously or consecutively. In this case, mixed testing strategies, staggered and non-staggered testing strategies, are used for testing the components. The objective of the present paper is to derive approximate formulas for the estimations of CCF probabilities of the components under mixed testing strategies, based on the basic parameter method [1,2]. The derived formulas were applied to four redundant check valves to demonstrate their appropriateness.

2. Common cause failure probabilities according to staggered and non-staggered testing strategies

The probability of a basic event involving k specific components in a common cause component group (CCCG) of size m for a staggered testing strategy, $Q_k^{(m)}$, is calculated by using the following equation [1,2,3]:

$$Q_k^{(m)} = (\alpha_k^{(m)} / {}_{m-1}C_{k-1}) Q_t \qquad (1)$$

where,
$\alpha_k^{(m)}$= fraction of the total frequency of the failure events that occur in a system involving the failure of k components due to a common cause.
${}_{m-1}C_{k-1}$=(m-1)!/[(m-k)!(k-1)!]
Q_t = total failure probability of a component in a CCCG due to all independent and common cause events.

A CCCG is a set of components that are considered to have a high potential for a failure due to a common cause. Q_t is represented as follows [1,2,3]:

$$Q_t = \sum_{k=1}^{m} {}_{m-1}C_{k-1} Q_k^{(m)} \qquad (2)$$

The maximum likelihood estimator of Q_k, by using the basic parameter method, is given as [1,2,3]

$$Q_k = n_k/N_k \qquad (3)$$

Where n_j represents the number of events involving j components in a failed state and is obtained by the summation of the j-th element of the impact vector, over all the events. n_1 is the sum of the first element and the adjusted independent events. Adjusted independent events are estimated by considering a difference in the system size between the original plant and the target plant. N_k is the number of demands on any k component in the CCCG.

For the case where the non-staggered testing is performed, the probability of a basic event involving k specific components in a CCCG of size m for a non-staggered testing strategy, Q_k^{NS}, can be represented as [1,2,3]

$$Q_k^{NS} = n_k/N_k = n_k/({}_mC_k N_D) \qquad (3)$$

where N_D is the number of demands for a system test.

For the case where the staggered testing is performed, the probability of a basic event involving k specific components in a CCCG of size m for a staggered testing strategy, Q_k^S, can be expressed as [1,2,3]

$$Q_k^S = n_k/N_k \approx n_k /[({}_{m-1}C_{k-1}) m N_D] \qquad (4)$$

3. Common cause failure probabilities of the components under mixed testing strategies

The number of components in the same CCCG within each train is the same, for any k component in the CCCG consisting of m redundant components, each success of any train tested in a single test episode results in ${}_mC_k - {}_{m-p}C_k$ tests. The p of ${}_{m-p}C_k$ denotes the number of components in the same CCCG within each train. Any failure of components in a train leads to a test of all the other components. Thus, the number of tests for any k component in the CCCG in a single test episode is ${}_mC_k$.

For any k component in the CCCG consisting of m redundant components, if the number of demands for the system test is N_D and the number of failed components is N_f (= $\sum_{j=1}^{m} n_j$), the number of demands on any k component in the CCCG, N_k, can be represented as follows:

N_k = Number of tests for the case of a success + Number of tests for the case of a failure

$$=[(m N_D /q) - N_f]({}_mC_k - {}_{m-p}C_k) + N_f({}_mC_k)$$
$$=(mN_D/q)({}_mC_k - {}_{m-p}C_k) + N_f({}_{m-p}C_k) \qquad (5)$$

In Eq. (5), q is obtained by dividing m by the number of trains. If all the m components are tested in a staggered manner, then q is equal to one.

For the case where an additional test is not performed for the observation of a failure for a tested component, N_k, can be expressed as

$$N_k = [(mN_D/q) - N_f]({}_mC_k - {}_{m-p}C_k) \qquad (6)$$

In Eq. (5) and Eq. (6), N_f is much smaller than mN_D/q. Hence, Eq. (5) and Eq. (6) can be represented as

$$N_k \approx (mN_D/q)({}_mC_k - {}_{m-p}C_k) \quad (7)$$

From Eq. (3), the probability of a basic event involving k specific components in a CCCG of size m for the mixed testing strategies, Q_k^{MIX}, can be expressed as

$$Q_k^{MIX} = n_k / N_k \approx n_k/[(mN_D/q)({}_mC_k - {}_{m-p}C_k)] \quad (8)$$

By using Eq. (2), Q_k^{MIX} can be represented as follows:

$$Q_k^{MIX} \approx Q_t[n_k / ({}_mC_k - {}_{m-p}C_k)] \Big/ \sum_{j=1}^{m} [n_j({}_{m-1}C_{j-1})/({}_mC_j - {}_{m-p}C_j)] \quad (9)$$

From Eq. (9) and Eq. (3), the ratio of a probability of a CCF event involving k specific components in a CCCG of size m for the mixed testing strategies to that for a non-staggered testing strategy can be given as

$$Q_k^{MIX} / Q_k^{NS} \approx (q/m)[{}_mC_k / ({}_mC_k - {}_{m-p}C_k)] \quad (10)$$

From Eq. (9) and Eq. (4), the ratio of a probability of a CCF event involving k specific components in a CCCG of size m for the mixed testing strategies to that for a staggered testing strategy can be expressed as

$$Q_k^{MIX} / Q_k^{S} \approx q[{}_{m-1}C_{k-1} / ({}_mC_k - {}_{m-p}C_k)] \quad (11)$$

The CCF probabilities for the components under the mixed testing strategies can be estimated by using Eq. (9), Eq. (10), or Eq. (11).

4. Concluding remarks

The derived approximate formulas for the estimations of the CCF probabilities under the mixed testing strategies were applied to the auxiliary feed water system (AFWS) for Ulchin Unit 3. As shown in Table 1, the estimated CCF probabilities of the four redundant check valves for the mixed testing strategies were higher than those for the staggered testing strategy, and lower than those for the non-staggered testing strategy. From this result, we can conclude that the developed formulas are applicable to the estimations of the CCF probabilities of components under the mixed testing strategies. Table 2 shows the estimated CCF probabilities for the mixed testing strategies by using Eqs. (9), (10), and (11). The CCF probabilities for the staggered and non-staggered testing schemes are calculated easily if the alpha factors or MGL parameters are given. Hence, for the estimations of the CCF probabilities for the mixed testing schemes, the use of Eq. (10) or Eq. (11) is better than use of Eq. (9).

Table 1. CCF probabilities for the three testing strategies

	Staggered Testing	Non-staggered Testing	Mixed Testing
Q_1	2.24E-04	2.23E-04	2.24E-04
Q_2	3.43E-07	6.82E-07	4.11E-07
Q_3	2.54E-08	7.58E-08	3.80E-08
Q_4	2.12E-09	8.42E-09	4.23E-09

Table 2. CCF probabilities for the mixed testing strategies

	Use of Eq. (9)	Use of Eq. (10)	Use of Eq. (11)
Q_1	2.24E-04	2.23E-04	2.24E-04
Q_2	4.11E-07	4.09E-07	4.11E-07
Q_3	3.80E-08	3.79E-08	3.81E-08
Q_4	4.23E-09	4.21E-09	4.23E-09

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