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Action Scenarios and Logic Trees

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Introduction

This is one of the documents of a series of publications, prepared by individual authors but discussed within the Joint Committee on Structural Safety (JCSS), in particular within its Working Party. The series up to now consists of the following titles:

Proposal for a Code for the Direct Use of Reliability Methods in Structural Design
O. Ditlevsen, H.O. Madsen

Estimation of Structural Properties by Testing for Use in Limit State Design
M. Kersken-Bradley, W. Maier, R. Rackwitz, A. Vrouwenvelder

Structural Performance Criteria
L. Östlund

Stochastic Modeling of Material Properties and Quality Control
M. Kersken-Bradley, R. Rackwitz

Design for Durability including Deterioration and Maintenance Procedures
G.I. Schuëller

Action Scenarios and Logic Trees
R. Giannini, P.E. Pinto, R. Rackwitz

Geometrical Variability in Structural Members and Systems
F. Casciati, I. Negri, R. Rackwitz

Bayesian Decision Analysis as a Tool for Structural Engineering Decisions
O. Ditlevsen

The papers are referred to as "Working Documents" since they generally give information on the state of development of certain concepts or subjects, rather than giving approved guidelines.

This paper deals with the application of logic tree analysis to structural design in the wide sense. Rather than pursueing the event sequence of subsequent local structural failures (which generally proves to be a rather short sequence), it is suggested to use logic tree analysis for
- *identifying relevant action scenarios*
- *deciding on design solutions*

This is illustrated by means of an interesting example.

This series of publications is intended to initiate discussions and exchange of comments. Comments may be sent to the Headquarter of IABSE, which will take care of sending these to the respective bodies of the JCSS.

Future papers of the JCSS will appear in appropriate international Engineering Journals. This series published by IABSE is closed.

The above papers are issued in honour of Professor Julio Ferry Borges, former President of the JCSS, expressing our deep appreciation and sincere thanks for successfully guiding the Joint Committee for more than 18 years.

The General Reporter of the JCSS:
M. Kersken-Bradley (until November 1990)
A. Vrouwenvelder (at present)

The President of the JCSS:
J. Schneider

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Action Scenarios and Logic Trees

1. Action scenarios

An action scenario can be defined in general terms as a particular combination of environmental physical phenomena (natural and man made) which is relevant for the assessment of the risk of a given system.

For the purpose of the analysis, the scenario will generally be modelled by means of a *vector* of random fields or processes. Each component of this vector can be thought of as representing a different physical action acting on the system. Examples of these components could be the (monovariate three-dimensional) random field of vertical superimposed loads on the floors of a building, the monovariate monodimensional random process of a point-like seismic acceleration, etc.

Ideally, the effects of the environment on the system should be analyzed using a model comprising both, so that any possible interaction between the two would be automatically included.

In practice, however, systems and environment are seldom, if ever, coupled in the analysis, and the latter is represented by means of a set of actions applied to the system. This requires generally further elaborations with respect to the free-field models of the actions and in some cases significant correlations need to be introduced between certain components which, in the absence of the construction, would be only slightly or even not correlated at all. A typical example of structure-induced correlation is that between wind velocity and snow accumulation on roofs.

While it can be assumed that in a near future sufficiently realistic standardized probabilistic models for the single physical actions will be made available to the designer, a proper coupling of the actions depending on the structure's existence (and also possibly on the structure's response) is to be considered as a part of the analysis, and it is thus under the responsibility of the designer.

The setting-up of an action scenario is hardly a subject amenable to a general formal treatment. The following statements can be used to advantage in some cases:

- **actions which are mathematically modeled as single (or as a process of) impulses do not combine temporally with each other. Therefore, if a system may be subjected to more than one impulsive action, the number of scenarios to be considered will be as large as the number of impulsive actions. Account should be taken of the fact that subsequent scenarios may find the system still partly damaged from the effect of the previous ones.**
- **an action needs not to be included in a scenario whenever its probability of occurrence with a significant potential for damage is negligible with respect to the accepted failure rate relative to the particular damage state of interest. In using this exclusion criterion however, account has to be taken of the fact that the accepted failure rate is, in general, dependent on the nature of the action causing it.**

2. Logic trees

The capability of a system to perform its intended functions can be effectively analyzed by using the concept of the "logic tree".

The definition of a logic tree can be given at different levels of generality, depending on the nature of the system. For this purpose, the following basic distinction is introduced.

2.1 Functional Systems

The systems of this class are composed of a number of identifiable subsystems, each one intended for a specific function. The subsystems may be of active or of stand-by type, and provide a degree of redundancy with respect to the loss of capacity of the system (parallel behavior).
Subsystems can be of different nature as, for ex., structural assemblages, mechanical systems made of pipings, pumps and valves, electrical systems, etc.: depending on the number and types of subsystems which fail, different levels of damage are attained by the system. Partial sequence of subsystem failures defines what is called a 'state' of the system.
As it will be explained in the following, the logic tree is essentially a graphic display of the various possibilities of system states. From the point of view of reliability quantification, applicable techniques vary depending on the behavior of the elementary sub-systems, in particular whether they can be reasonably represented with a binary state, i.e., either perfectly functioning or failed.
If this assumption is acceptable it is well known that a general representation of the system logic is given by its minimum cut set (parallel subsystems in series) or, dually, by its minimum path to failure (serial subsystems in parallel).

2.2 Structural Systems

Any structure composed by more than a single element and whose purpose is to offer direct resistance to actions belongs to this class.
Single structural elements, or groups there of, could still be regarded as subsystems, as could sets of failed elements be considered as defining 'states' of the system.

There are reasons, however, that make this approach more difficult to implement for this class of systems.

Firstly, the functional logic of these systems is related solely to their structural behavior, and so it is automatically included in the algorithm used for the analysis. As a consequence, it is often difficult to separate, in the form of a sequence of elemental failures, the contribution of each subsystem to the global performance of the system.

Furthermore, structural elements generally possess a mechanical behavior which is history-dependent and degradates in a continuous fashion prior to reaching complete failure. This implies that a given damage state of the structure (ex.: a certain crack width) can result from infinitely many combinations of degraded elements states, making it unfeasible to enumerate them.

3. Logic trees for functional systems

The construction of a logic tree is similar to that of the "accident sequences trees", which are widely employed for the safety analyses of generic non structural systems. A brief outline of the technique is given by making reference to the figure below.

In the presentation of Fig. 1, the so-called "initiating event" consists of the action scenario itself. In other versions, the sequence tree starts with an "initiated event", which is a (probabilized) event (ex.: rupture of a piping) triggering the intervention of the various subsystems, in their capacity of accident mitigators.

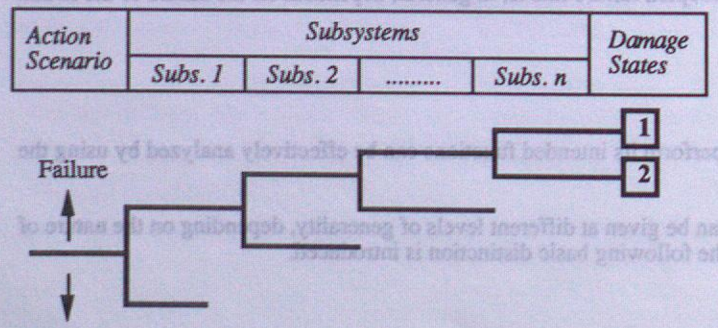


Fig. 1 Example of a classical accident sequence tree

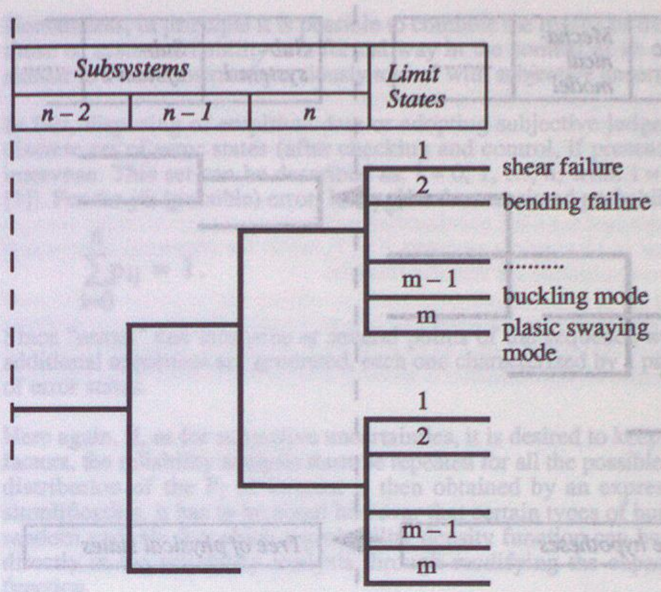


Fig. 2 Accident sequence tree when consequences are structural failure

The tree in Fig. 1 must be constructed so as to contain *all* the logically *possible* sequences the system may actually pass through. Each sequence ends at a different final state, which by definition is referred to as 'damage state', even if this term actually includes states which are compatible with the functioning of the system.

Quantitative probabilistic assessment of each sequence, can be performed through the use of FORM or SORM methods for system reliability. The result is the probability of attaining any of the damage states under the assumed actions scenario.

In cases when the system comprises important (safety-related) structural parts, it occurs frequently that the final portion of the tree in Fig. 1 is modified. Since the final interest focusses on the conditions of the structural part, a number of pertinent limit-states are introduced (the term: "limit-state" is meant to include the concept of 'failure mode') and the result which is sought consists of the exceedance probability of every limit-state of interest. The end of the tree looks in this case as shown in Fig. 2.

3.1 Uncertainties and randomnesses

In cases where no completely rigorous physical models are available, either for the actions or for the subsystems behavior, some of the probabilistic information which is fed in the analysis is inevitably of the subjective nature.

Though the distinction between frequentist and subjective uncertainty is not always clear-cut, and both types may coexist in the same variables or choices, for some of them their predominantly subjective nature is unmistakable, and there is a recognized convenience of keeping separate their contribution to the final probability estimate. In this way subjectivity is made more explicit, and is therefore open to external review.

The tree format lends itself naturally to incorporate the existence of alternative choices. It is only required to introduce for each type of uncertainty as many additional branches as is the number of possible alternatives.

The various sources of subjective uncertainty can be arranged together in sequential order and considered as alternative conditional hypotheses for the analyses to follow. The entire logic tree would thus be split in two parts: a pre-tree whose branches represent alternative hypotheses, followed by the usual tree whose branches represent physical conditions of the system.

The appearance of such a composite tree is exemplified in Fig. 3.

Each sequence in the pre-tree corresponds to a particular set of hypotheses. Since it is assumed that a normalized weight can be attributed to every single alternative, a probability value is easily obtained for the entire sequence.

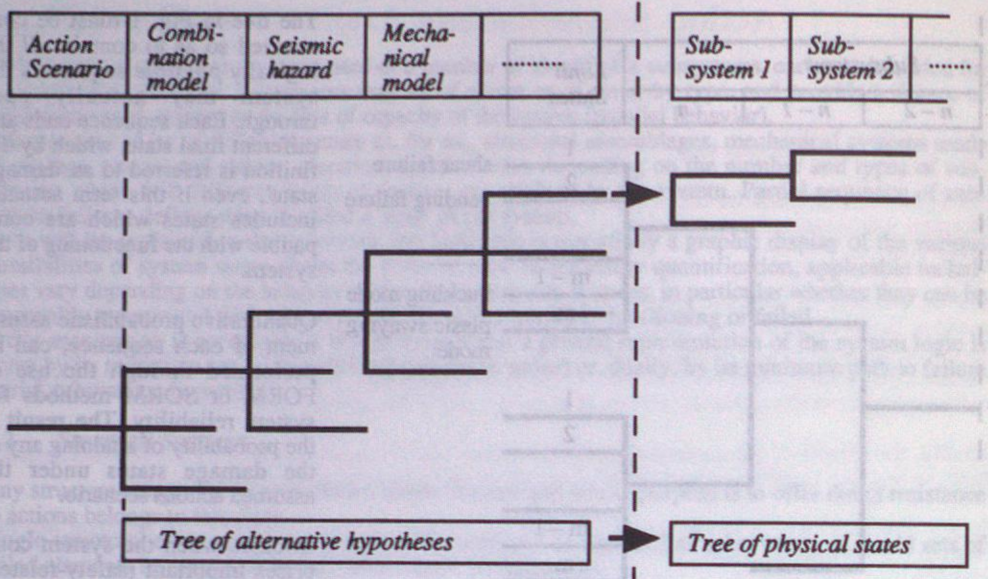
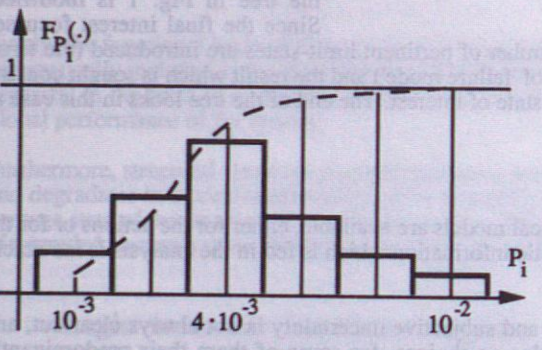


Fig. 3 Composite logic tree



P_i = Probability of exceeding the ith limit state

Fig. 4 Distribution of the probability of exceeding a limit state due to subjective uncertainties

Given a particular set of initial choices, the safety analysis of the system, carried out according to the second part of the tree, yields exceedance probability values for the limit states of interest. By repeating the analysis for all the combinations of initial choices, a histogram of the exceedance probabilities thus obtained can be constructed, as shown in Fig.4. With the index i indicating the ith failure mode, the distribution of the probability of this mode can then be evaluated as:

$$F_{pi}(x) = \sum_{\gamma \leq x} P_i(\gamma) \qquad 1)$$

where the sum extends to the calculated exceedance probability values less than or equal to x.

3.2 Human factors

Human involvement in the various phases of design, construction, operation and maintenance of a functional or structural facility introduces uncertainties resulting from human errors and/or human intervention strategies and procedures [1].

Accounting for both of these interacting phenomena requires a set of decisions, as regards: the modelling, i.e. the identification of the human errors (omission and commission) and of their nature (reversible/irreversible, systematic/random); the quantification of the probability of their occurrence. An effective modelling, that is a prerequisite for a valid quantification, represents a very difficult task, and completeness is hardly achieved in complex situations. To circumvent this problem, in some cases the attention can be focussed on the modelling the reliability of the error correction measures.

Nonetheless, in principle it is possible to combine the results of the human reliability assessment with those of system reliability in a formal way in the context of an event tree model, much along lines similar to those illustrated previously to deal with subjective uncertainties.

In fact, disposing of empirical data or adopting subjective judgement, it is sufficient to consider a discrete set of error states (after checking and control, if present) for each event in which humans intervene. This set can be described as: $i = 0, 1, \ldots, n$; with: $i = 0$ indicating no error content (see [1]). For the jth (possible) error, let $\{p_{ij}\}$ be the associated probability set, with:

$$\sum_{i=0}^{n} p_{ij} = 1.$$

Since "errors" can intervene at several points of the sequence with various degrees of "intensity", additional sequences are generated, each one characterized by a particular, probabilized, combination of error states.

Here again, if, as for subjective uncertainties, it is desired to keep it separate the effect of the human factors, the reliability analysis must be repeated for all the possible combinations of error states, and a distribution of the P_f of interest is then obtained by an expression analogous to expr. 1). As a simplification, it has to be noted however that certain types of human errors can be represented by a random variable for which a probability density function can be postulated, and then incorporated directly in the reliability analysis through modifying the capacity or demand terms of the state function.

In the aforementioned procedure, the calibration of the terms p_{ij} is very difficult in situations other than those involving proceduralized and relatively simple human actions. This difficulty is more evident in the case of structural systems, for which the probability of error occurrence, control and consequence strictly depends on the behavioral model and on realistic and representative assumptions on the element response in different circumstances.

4. Logic trees for structural systems

It has been anticipated already that for purely structural systems made up of real elements, the second part of the composite tree, i. e., the one describing the possible physical states of the system in terms of the failed elements, is both difficult to construct and less meaningful.

Nevertheless, some approaches using a tree format can be found in the literature related to structural reliability assessment, that are applied, with relative success, to structural systems with multiple failure modes and different member behavior (see [2], [3], [4] for comprehensive reviews). This kind of tree analysis is based on the assumption that each state of the system can be expressed - unambiguously - as a function of the states of its elements, and that it can be reached through different ordered sequences of elemental failures, or, more generally, of transitions from one state of a member to another.

Application of these techniques, however, imposes rather severe limitations on both the loading and structural models. This is so because all heuristic strategies that can be adopted to produce different failure sequences to appear are in principle dependent on complex phenomena as the interaction between the occurrence of the various loads, their variation in time and the progressive degradation of the elements, and the redistribution of internal forces among the remaining elements after partial or total failure of some of them.

In practice, solutions to the problem (i.e., modelling of the event tree, and quantification of the probability of occurrence of each sequence) are available providing that: the structural model is of a discrete type, so that local failures may occur only in a finite number of points; for each element of the system a (set of) safe state(s) and a failure state can be defined, according to a multistate mechanical model; the state transitions are considered as irreversible; the loading path and sequence are uniquely defined (e.g., the loads are proportionally increasing); the actions are such as to generate a static response, and the progressive system failure does not cause dynamic effects.

A source of difficulty proper to the tree approach lies in the numerical evaluation of the probability of occurrence of the various sequences and of the global failure probability, because large statistical correlation may be present among the different sequences, due to the common loading and the correlations between resistance variables.

In general, exact results can be established for ideal plastic structural systems (as reported for example in [5]), as well as for the special case of ideal brittle elements [6] [7], while for structural behaviors of more realistic types, only approximate solutions are actually feasible.

A final comment, however, is appropriate regarding the use of tree formats for structural systems: these approaches differ conceptually from the logic trees discussed in par. 2.1. In fact, they are operational algorithms, specialized for selected behavioral models, and do not describe any particular logic of the structure.

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6. Numerical illustration of a Failure Tree Analysis

The object of investigation is an existing gravity dam made out of natural brick work. A failure tree approach is used to quantify the present level of safety, as described in detail in ref. [8]. Starting from an initiating event (leading event) one has to follow all the possible paths, each one corresponding to a particular combination of subsystem behavior. In case of the dam the leading event is an extreme flood and "normal" ice pressure $\{XF \cap I\}$. The different states of the system are represented by events like {SF} (spill-way failed), {OD} (outlet opening delayed), {GO} (ground outlet open), {SO} (service outlet open). Each of these and their complementary events have some probability and may depend on each other.

Two failure states of the gravity dam are investigated: one is the exceedance of the resistance in the mortar joint (R), and the other one is the overturning of the dam (T). All combinations of system states, i.e. branches of the failure tree are shown in Fig.5 on the next two pages together with the probability of each event $P(E_{i,j})$ (ith event, jth branch) (upper boxes) and the cut along each path.

$$P = P\left(\bigcap_{i=1}^{l} E_{i,j}\right)$$ (lower boxes) both in ß scale

Finally, system failure probability is calculated by

$$P_{sys} = P\left(\bigcup_{j=1}^{l} \bigcap_{i=1}^{k} E_{i,j}\right)$$

The probabilities evaluated in this way are obviously conditional to the occurrence of the initiating event.

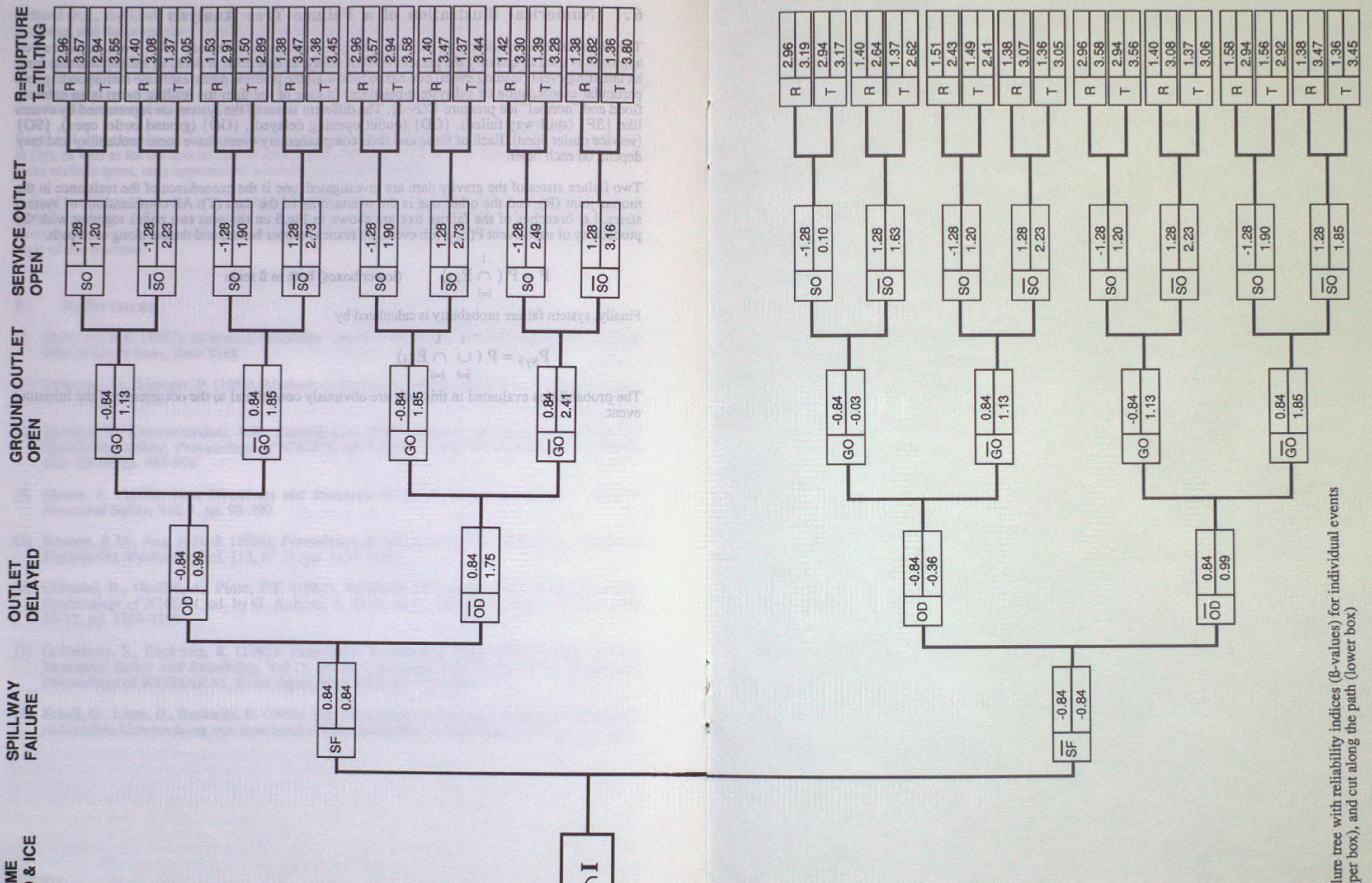

Fig. 5 Failure tree with reliability indices (ß-values) for individual events (upper box), and cut along the path (lower box)