Transactions of the Japan Welding Society Vol. 11, No. 1, April 1980

An Application of Fault Tree Analysis to Weld Cracking*

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Abstract

As welded structures increase their sizes, and their operating conditions become more and more severe, the problem of the quality assurance in weldments becomes increasingly important. Therefore, this paper attempts to apply Fault Tree Analysis, one of systems theory techniques, to a simple case of weld cracking in a butt-welded joint to examine the usefulness of this technique, since the prevention of weld cracking is directly related to the improvement in the safety and reliability of weldments. It is concluded that although there are not a few problems left to be solved for Fault Tree Analysis to provide a fully reasonable decision-making basis for the quality assurance of weldments, FTA is still expected to be quite a powerful tool for the analysis of quality assurance if such practical expedient methods as described in this paper are introduced into FTA.

1. Introduction

As welded structures increase their sizes, and their operating conditions become more and more severe, the problem of safety and reliability becomes more and more important. Since the fractures of large structures lead to quite serious consequences and large scale structures cannot be constructed without welding, the problem of quality assurance in weldments becomes increasingly important. As the technique of welding is concerned with quite wide areas of engineering the coordination between the related engineering areas is considered indispensable for improving the quality of welding, not to mention the improvement in each engineering technique. Therefore, the introduction of systems approach is believed to be necessary for this purpose.

In this paper, an attempt is made to apply Fault Tree Analysis (FTA), one of systems theory techniques, to a simple case of weld cracking in a butt welded joint and the usefulness of this technique is examined, because weld cracking is directly related to the structural integrity of a welded structure.

2. FTA: its concepts and features

First, the concepts and features of FTA are explained briefly. FTA is a kind of graphical representation of a failure logic using Boolean algebra. In FTA, the undesired event (system failure) is selected as the Top Event and Fault Tree can be constructed by logically developing this Top Event. i.e., Top Event is connected through logic symbols with the lower rank events which are the direct cause of this event. These lower rank events are further connected with the events one rank lower using logic symbols. This process is repeated rank after rank until Basic Events are reached which cannot be developed any further. In FTA, Top Event and Intermediate Events are represented by rectangles and Basic Events are represented by circles. A most simple case is shown in Fig. 1 and Fig. 2 for illustration. In this case the event "no light" is selected as Top Event. Although Fig. 2 shows qualitative failure logic, quantitative analysis is also possible, if the probabilities of the occurrences of Basic Events are given. In the case of Fig. 2, if the probabilities of the occurrences of the failures of switches 1, 2 and 3 are given as P_1, P_2 and P_3 respectively, then the probability P_T of the occurrence of Top Event T can be calculated according to the logic symbols as $P_T = 1-(1-P_A)\times(1-P_B) = 1-(1-P_1)\times(1-P_2\times P_3)$. Another advantage of FTA is that it can include human errors in Basic Events. As the quality of welding depends not a little on the skills of welders and/or NDI technicians, FTA is expected from this point too to provide quite a powerful

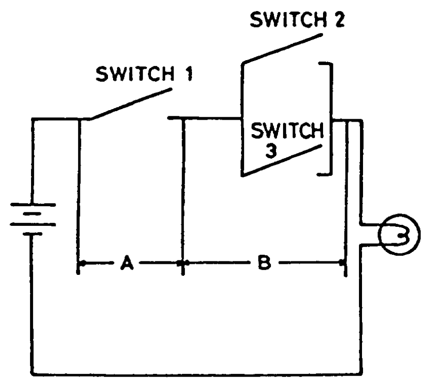

Fig. 1 Sample system

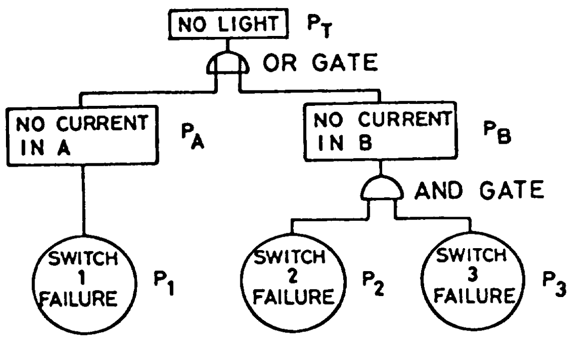

Fig. 2 Fault tree for sample system of Fig. 1

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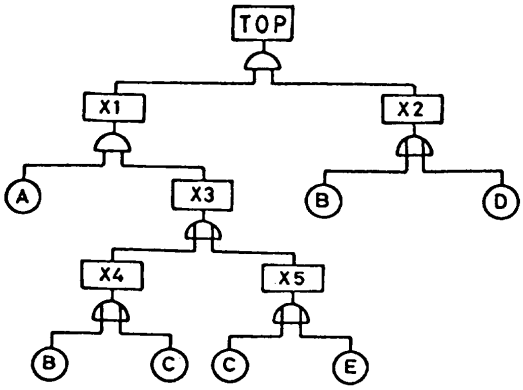

Fig. 3 Sample fault tree

tool for the analysis of quality assurance in weldments.

In many of the phenomena in welding, a certain event is related with many other events so that the relation between events is quite complicated. Fig. 3 shows an example of such a fault tree in which the same Basic Event is related to several different Intermediate Events. This type of fault tree is more often than not observed in the analysis of the phenomena in welding. Although this example is a very simple case, it is not easy to make out how Basic Events A-E are related to the occurrence of the Top Event T, because Basic Event B is related not only to X2 but also to X4, and Basic Event C is related to both X4 and X5, so that X2 and X4, and X4 and X5 are not independent of each other. Terefore, it is difficult to pass judgment instantly on what measures we should take to prevent the occurrence of the Top Event. But in FTA, we can easily find out how we can prevent the occurrence of the Top Event, if we utilize the concept of minimal cut sets. A minimal cut set is the smallest set of Basic Events which is necessary and sufficient for the Top Event to occur. The minimal cut sets of the fault tree of Fig. 3 are {A, B}, {A, C, D}, {A, D, E} as shown in Fig. 4. The Top Event T occurs if any one of these occurs. Therefore, to prevent the occurrence of the Top Event, it is necessary to prevent the occurrences of all minimal cut sets, i.e., K1, K2 and K3, and to prevent K1 from occurring, the occurrence of either A or B must be prevented.

But in order to take the best effective measures to improve the reliability, it is not sufficient only to know how qualitatively each Basic Event is related to the occurrence of the Top Event, but it must also be made clear how much quantitatively each Basic Event influences the occurrence of the Top Event.

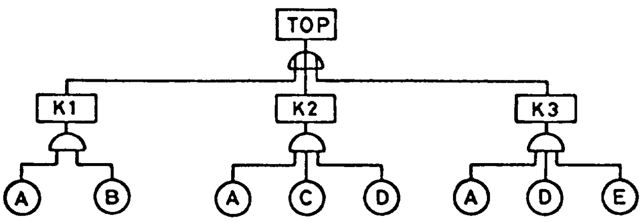

Fig. 4 Boolean equivalent fault tree of Fig. 3 using minimal cut sets

For such evaluation of the importance of Basic Events, three measures of importance i.e., structural importance, probability importance, and criticality importance are used in FTA. Structural importance evaluates the importance of a certain Basic Event quantitatively by counting up the number of critical cut vectors, i.e., by counting the number of cases is which the state of the Top Event changes from "not occurred" to "occurred" by changing the state of this Basic Event from "not occurred" to "occurred," while keeping the states of all other Basic Events as they are. Structural importance is unique, therefore, in that it can be evaluated as long as the structure (the shape of a tree and the logic symbols used) of a fault tree is given. Consequently, it can be evaluated even if quantitative data for each Basic Event are not given. Probability importance is defined by the probability of the occurrence of the state of the critical cut vector while structural importance is defined by the number of critical cut vectors. Criticality importance corresponds to the failure diagnosis using Bayes theorem, and it determines how much the occurrence of the Top Event is attributable to each Basic Event on the basis of probabilities.

The details in the technique of FTA (such as how to obtain minimal cut sets, etc.) are described in Ref. (1)-(5).

3. Application of FTA to cold cracking in a butt welded joint

To examine the usefulness of the technique, an attempt is made to apply FTA to cold cracking in a butt welded joint. To simplify the analysis, such a simple case is treated that cold cracking occurs in a butt welded specimen when one layer shielded metal arc welding is carried out in a laboratory; and to simplify further, it is assumed that (1) the diameter of the electrode is fixed, (2) the electrode is used immediately after drying and (3) no special post weld heat treatment is applied for the reason that although such problems as how electrodes are stored or how long it is from the time of drying when the electrodes are used are quite important and the problem of PWHT is quite serious especially in the case of heavy section low alloy steel, these problems can be solved by extending this analysis and the principles of such analyses are just the same. In fact, the validity of FTA for the particular case of transverse weld cracking in a heavy section low alloy steel is already discussed elsewhere by the present author in relation with the omission of intermediate PWHT (See Ref. (6)).

Fig. 5 shows one example of the fault tree for this problem. The contents of the Top Event and Basic Events are shown in Table 1 and the contents of Intermediate Events are shown in Table 2. Although these tables show terms alone for Basic and Intermediate Events, it is implicit that these items represent phenomena that lead to an occurrence of the Top Event. And a diamond in Fig. 5 represents a fault

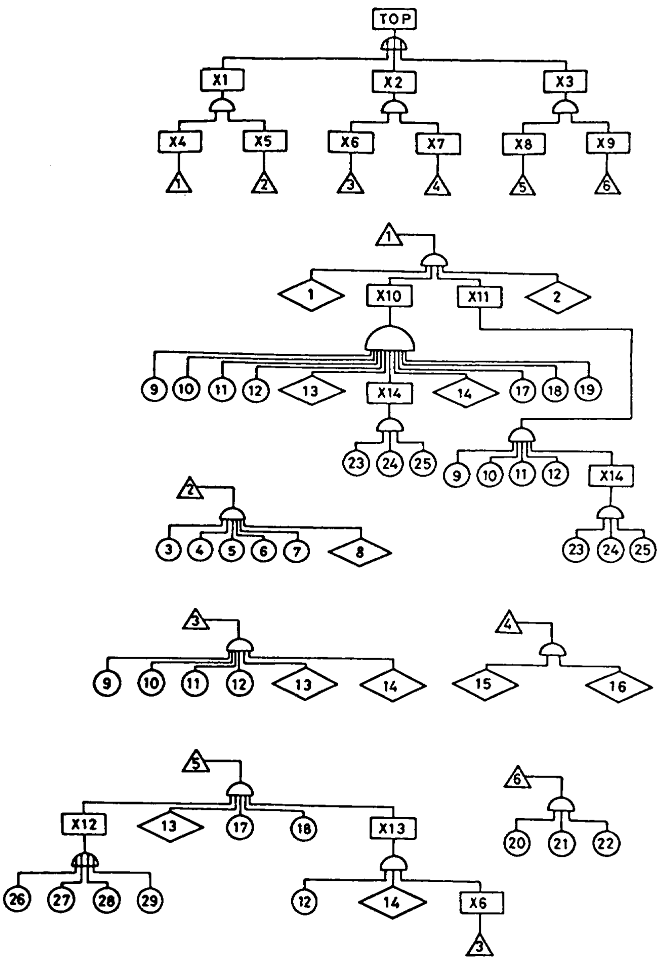

Fig. 5 Fault tree for cold cracking in butt welded joint

Table 1 Top Event and Basic Events

TOP EVENT=COLD CRACKING OCCURS IN BUTT WELDED SPECIMEN
1=HOLD TIME OF PEAK TEMPERATURE
2=HEATING RATE
3=CARBON
4=MANAGNESE
5=NICKEL
6=CHROMIUM
7=MOLYBDENUM
8=OTHER HARDENABLE ELEMENTS
9=WELDING SPEED
10=WELDING CURRENT
11=WELDING VOLTAGE
12=THICKNESS
13=ELECTRODE MANIPULATION
14=TYPE OF GROOVE
15=USAGE OF FIXTURE
16=DIMENSIONS OF PLATE (THICKNESS NOT INCLUDED)
17=PREHEATING
18=INITIAL TEMPERATURE OF STEEL
19=THERMAL RADIATION FROM SURFACE
20=HUMIDITY IN WELDING ENVIRONMENT
21=TYPE OF ELECTRODE (LOW HYDROGEN TYPE OR NOT)
22=DRYING OF ELECTRODE
23=SPECIFIC HEAT
24=THERMAL CONDUCTIVITY
25=DENSITY
26=STRUCTURAL DISCONTINUITY
27=GRAIN BOUNDARY
28=NONMETALLIC INCLUSION
29=LATTICE DEFECT

Table 2 Intermediate Events

X1 =HARDENING OF HAZ
X2 =INTENSITY OF RESTRAINT
X3 =HYDROGEN
X4 =WELDING THERMAL CYCLE
X5 =HARDENABILITY OF MATERIAL
X6 =INTERNAL CONSTRAINT
X7 =EXTERNAL CONSTRAINT
X8 =HYDROGEN DIFFUSION IN WELD ZONE
X9 =HYDROGEN CONTENT IN WELD ZONE
X10=COOLING RATE
X11=PEAK TEMPERATURE
X12=DEFECT
X13=LOCAL STRESS
X14=THERMAL PROPERTIES OF MATERIAL

event that is not developed to its cause, and a triangle is a "connecting" or "transfer" symbol.

In Fig. 5, OR gate is used for the logic symbol which connects the Top Event and Intermediate Events X1, X2 and X3. There might be opinions, however, against the usage of OR gate here for the reason that cold cracking never occurs in such a simple manner that its cause is merely X1 or X2 or X3 alone, but that it occurs due to the quite complicated effects of X1, X2 and X3 combined. But it must be emphasized that the primary aim of applying FTA to cracking problems in such a case as this is to find out how we can prevent the occurrence of cracking. At least it is on the safe side and cracking can be prevented if we let none of X1, X2 and X3 lead to cracking. Therefore, OR gate is used here, considering its duality.

As various kinds of logic symbols can be used in FTA, it is possible to express to a large extent the actual failure logic as truly as possible, but it must be noted that FTA in itself is design-oriented and that one of the most important advantages of FTA is that we can find out an effective policy immediately by simplifying extremely complicated phenomena as much as possible. It seems, therefore, that we should make our efforts to simplify the phenomena as much as possible by making the most of the advantage of Boolean algebra. Viewed in this light, the use of the complicated logic symbols should be avoided as much as possible because minimal cut sets are difficult to obtain.

Fig. 6 is the Boolean equivalent fault tree of Fig. 5

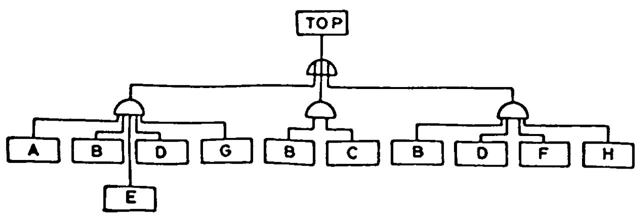

Fig. 6 Boolean equivalent fault tree of Fig. 5 using minimal cut sets

using minimal cut sets. Three minimal cut sets are obtained in this case; {A, B, D, E, G}, {B, C}, {B, D, F, H}. The contents of A-H consist of the following Basic Events: A={1, 2, 3, 4, 5, 6, 7, 8}, B={9, 10, 11, 12, 13, 14}, C={15, 16}, D={17, 18}, E={19}, F={20, 21, 22}, G={23, 24, 25}, H={26, 27, 28, 29}. The structural importances of A-H are calculated and their ratios are A:B:C:D:E:F:G:H=3:67:53:11:3:9:3:4. Thus it is known that B and C are the most important factors in the occurrence of cold cracking and that D and F are next important. This conclusion can be anticipated at least qualitatively from the figure. As Basic Event B appears in all minimal cut sets, it is most crucial, and D is also considerably critical since D appears in two minimal cut sets. And the middle minimal cut set in the figure consists of only two Basic Events B and C, so that C is expected to be as important as B. As for the contents of B, C, D, and F, B represents welding condition (voltage, current, speed), thickness, manipulation of the electrode, and edge preparation. It can be understood that B is important, if we note that greater care must be taken for thicker plates, and that welding condition is directly related to heat input which in the case of high strength steels is limited in the codes to prevent weld cracking[7], and that manipulation of the electrode is also directly related to heat input, so that there are cases of cracking by mismanipulation[8], and that high local stress produces cracking, even if macroscopic constraint of the joint is the same[9]. C is a factor concerned with the constraint of the joint, and D relates to preheating. F is a factor concerned with diffusible hydrogen. The results of this analysis are considered to agree at least fundamentally with the concept of the study group of weld cracking of JSSC[10], hence the validity of the present approach is confirmed.

Now, it is easily known by intuition that the event E={19} is relatively of small importance. In fact, Fig. 6 indicates that the importance of E is small. For such events, we had better make our efforts to exclude them from Basic Events and to simplify the analysis. Although an increase in the number of Basic Events in such a simple case as this does not make the analysis appreciably difficult, an increase in the number of Basic Events in large scale problems makes the analysis excedingly difficult. Therefore, it is considered more appropriate to estimate the crucial factors first by approximation, and then to carry out more detailed or more exact analyses as required.

It must be emphasized that although FTA can pick out the crucial factors, the concrete contents of the measures must be determined by using other techniques. For example, what type of groove can prevent the occurrence of weld cracking in terms of mechanics must be determined by such a method as numerical stress analysis.

4. Discussion

As is well known, the factors affecting the quality of welding are so many and diverse that multifarious fields are involved. So complicated are the phenomena of welding that in the field of welding, there are not a few problems left still unsolved quantitatively. But the present situation is such that the failure logics in the phenomena of welding are rapidly being revealed. As this simple illustrative example shows, FTA provides an effective tool for decision-making as to what measures should be taken to prevent the failure even if the quantitative data of Basic Events are not available, as long as its failure logic is clear. Therefore, FTA is expected to be quite a powerful tool for securing the quality of welding, and therefore for improving the safety and reliability of a welded structure.

Although a fault tree represents a failure logic, it is most likely in reality that different engineers construct different fault trees according to their engineering backgrounds or fields. In such a case, the most appropriate fault tree would be obtained by discussing and comparing these fault trees among engineers. If engineers of different fields have thorough discussions in terms of FTA during this process of constructing a final fault tree, then it is expected that cases such as poor communication among engineers or omission of important technical information or knowledge of the past which often lead to accidents as history shows might possibly be reduced considerably.

In any event, to make adequate decisions based on FTA, it is necessary that a failure logic be expressed appropriately by a fault tree. This point is quite important when the importance of Basic Events is evaluated based on structural importance, because structural importance is determined solely by the structure of a fault tree. For example, if one Intermediate Event is developed in more detail than other Intermediate Events, there is a risk of evaluating not very important Basic Events, as if they were quite important. Thus, in order to make reasonable decisions using FTA, it is necessary that (1) the constructed fault tree constitute an adequate hirearchy and that (2) the logic symbols be properly selected. As to the point (1), it seems that any definite systematic method of constructing an adequate hierarchical fault tree has not been developed yet, so that it is considered necessary to render much efforts to develop such mathematical methods. But if we consider a practical solution apart from rigorous mathematical discussion, then such methods may be adopted as evaluating the importance of Basic Events using criticality importance by having different engineers of different fields assign subjective marks to each Basic Event, and by collecting the "considered to be most appropriate" data through the comparison and examination of the above mentioned marks. By using such an expedient method, fairly good evaluation of importance is expected to be possible at least for practical applications. As to the point (2), the present FTA is constructed based on two-value logic, but most of the strength problems cannot be expressed fully by two-value logic alone. Therefore, efforts are considered necessary to develop a new FTA by extending the logic from two-value to multi-value.

5. Summary

As welded structures increase their sizes, and their operating conditions become more and more severe, the problem of the quality assurance of welds becomes increasingly important. This paper attempts to apply Fault Tree Analysis to a most simple case of weld cracking and examine the usefulness of this technique, since weld cracking is directly related to the structural integrity of a welded structure.

Although there are not a few problems left to be solved for FTA to provide a fully reasonable decision-making basis for the quality assurance of welds, FTA is expected to provide quite a powerful tool for the analysis of the quality assurance in practical applications, if such expedient methods as described in this paper are introduced into FTA.

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