# Fault Collapsing For Digital Circuits Based On Relations Between Stuck-At Faults *

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## ABSTRACT

A way for fault collapsing is proposed for digital circuits based on the relations of fault equivalence and fault dominance. A new notion **of strict structural fault dominance** is proposed for single stuck-at faults on input/output lines of logical gates. Experiments are conducted on combinational circuits of ISCAS'85 and combinational parts of sequential benchmark circuits of ISCAS'89 benchmark circuits. Fault collapsing for most of the circuits is about 60-70%.

## Keywords

stuck-at fault, fault collapsing, equivalence, strict dominance

## 1. INTRODUCTION

Fault collapsing is an approach to alleviate the difficulties connected with the development of test sets for digital circuits. Since it is well-known (see e.g. [1]) that the generation of a test for a single stuck-at fault even for an input line of a combinational circuit is a very difficult problem, then any possible reduction for the number of faults needing development of test sets, is a great benefit. That is why many authors have done research on this topic and some algorithms were proposed for fault collapsing [2]-[4]. As a result, the number of lines needing development of test sets was reduced sometimes up to 50% or even more. Most of the proposed approaches that were classified as structural and functional refer to structural one when the relations of ***equivalence*** and ***dominance*** were defined between faults on input and output lines of logical gates. An extension of those notions, namely functional equivalence and functional dominance were also defined between any lines in a digital circuit allowing increase the percentage of fault collapsing [2]-[4]. At the same time, functional fault collapsing is a more difficult approach requiring availability of fast commercial programs for test generation of all stuck-at faults on every line in the circuit.

In this paper traditional structural fault collapsing is considered for combinational circuits. Applying a tree-based graph approach to the classical stuck-at faults on gate input/outputs of ISCAS85 and full-scan ISCAS89 benchmark circuits we collapsed the fault sets at average for 60-70%% of faults. The run-time of the algorithm is very fast taking a few seconds at average for a circuit. The results are given in Tables 1 and 2 for ISCAS85 and ISCAS'89 benchmark circuits, respectively. Note that in this work the algorithm works only a few seconds for most of the combinational and sequential circuits from ISCAS'85 and ISCAS'89.

In particular, in this paper the notion of "***strict structural dominance",*** an extension of the dominance relation, is introduced.

We showed that although strict dominance applied alone brings to a smaller percentage of fault collapsing than the equivalence relation but, however, when both of the relations are applied then better, than previously known results, can be obtained. Thus, for ISCAS'85 combinational benchmark circuits, most of the results coincide with that of the previously known best results but, however, for a few circuits better results were obtained. For example, for c7552 previously 59.14% and 59.15% of collapsing were obtained, but in our work we obtained 59.41%. For c2670, previously 56.07% and 56.08% of fault collapsing were obtained respectively. In our work we obtained 58.27% of fault collapsing. We applied this approach also for the combinational parts of ISCAS'89 benchmark circuits (full-scan approach). The obtained results were good too. Run time of our program for almost all circuits is a few seconds.

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## 2. MAIN DEFINITIONS

All necessary definitions of fault collapsing and strict dominance can be found in [2]-[4]. In the sequel, we shall use the notation A/c to denote a line A stuck-at-c, c ∈ {0,1}. The two concepts widely used in structural fault collapsing are (Structural) ***Fault Equivalence*** and (Structural) ***Fault Dominance***. They were defined in [2] as follows:

**Definition 1. (Structural Fault Equivalence)** Two single stuck-at faults α and β on an input/output line of a logical gate ***G*** in a circuit C are said to be structurally equivalent if and only if T(C/α) = T(C/β), where T(C/α) and T(C/β) are the complete test-sets for faults α and β respectively.

As to fault collapsing, when faults α and β are equivalent, it is sufficient for removing one of the faults α or β.

**Definition 2. (Structural Fault Dominance)** A fault α on the output of a logical gate ***G*** is said to "structurally dominate" another fault β on an input of gate ***G*** if T(C/β) ≤ T(C/α), i.e. all test vectors from T(C/β) are contained also in test-set T(C/α).

In such a case, all the tests for β can detect α as well. Then it means fault α can be collapsed from the fault list and a shorter test-set T(C/β) can detect both faults α and β.

Note that two faults will be equivalent if they dominate each other, i.e. T(C/β) ≤ T(C/α) and
T(C/α) ≤ T(C/β). Thus, T(C/β) = T(C/α), i.e. the test-sets of both faults coincide exactly.

**Definition 3. (Structural strict dominance).** A fault α on the output of a logical gate ***G*** is said "to dominate structurally and strictly" another fault β on an input of gate ***G*** if α structurally dominates fault β but β does not structurally dominate α.

**Lemma 1.** ***The output of either of the logical gates AND, OR, NAND and NOR strictly dominates each input of the gate.***

**Lemma 2.** For the logical gate ***XOR***, as well as the logical elements ***INVERTER*** and ***BUFFER,*** there is no relation of strict dominance between their input and output lines.

## 3. BRIEF DESCRIPTION OF THE MAIN ALGORITHM

For each gate we construct the so-called "tree of strict dominance". Then for each combinational circuit we construct its "directed graph representation". Then an algorithm is proposed for reduction of the number of faults by using the relations of ***strict dominance*** and equivalence.

Note that fan-outs of the circuit-graph are also taken into account. The complexity of the algorithm is O(nm) where n is the number of all vertices of the circuit-graph, and m is the maximum number of inputs for all gates in the circuit.

**Table 1.** *Results for combinational circuits from ISCAS85*

| Circuit | Number Of faults | Number of collapsed faults | | | Reduction (%) | Run time (sec.) |
|---|---|---|---|---|---|---|
| | | Equi-valence | Dominance | Equivalence & strict dominance | Equivalence & Strict dominance | |
| **C17** | **34** | **-** | **-** | **18** | **52.9** | **1** |
| **C432** | **864** | **524** | **458** | **469** | **48.03** | **1** |
| **C499** | **998** | **758** | **730** | **604** | **29.26** | **1** |
| **C880** | **1760** | **942** | **763** | **1015** | **57.67** | **3** |
| **C1355** | **2710** | **1574** | **1234** | **1500** | **55.35** | **3** |
| **C1908** | **3816** | **1879** | **1568** | **2251** | **59** | **4** |
| **C2670•** | **5340** | **2747** | **2324** | **3045** | **58.99** | **6** |
| **C3540** | **7080** | **3428** | **2882** | **4304** | **60.79** | **8** |
| **C5315** | **10630** | **5350** | **4530** | **6138** | **57.74** | **9** |
| **C6288** | **12576** | **7744** | **5840** | **6752** | **53.69** | **8** |
| **C7552•** | **15104** | **7550** | **6163** | **8973** | **59.4** | **12** |

• For the mentioned circuits the number of faults in our work and in [2]-[4] differ due to the unknown possible modifications of the circuits in [2]-[4]. There were no details given.

We obtained good results also for the combinational parts of sequential benchmark circuits from ISCAS'89. The results are shown in Table 2. For some circuits more than 70% collapsing is obtained.

**Table 2.** ***Results for combinational parts of sequential circuits from ISCAS89***

| Circuit | Number Of faults | Number of collapsed faults | | | Reduction (%) | Run time (sec.) |
|---|---|---|---|---|---|---|
| | | Equi-valence | Dominance | Equivalence & strict dominance | Equivalence & Strict dominance | |
| **S208** | **436** | **217** | **175** | **276** | **63.3** | 1 |
| **S298** | **596** | **308** | **266** | **336** | **56.4** | 1 |
| **S344** | **670** | **342** | **277** | **407** | **60.7** | 1 |
| **S349** | **680** | **350** | **283** | **412** | **60.5** | 1 |
| **S382** | **764** | **399** | **328** | **459** | **60.1** | 1 |
| **S386** | **772** | **384** | **295** | **495** | **64.1** | 1 |
| **S400** | **806** | **426** | **354** | **481** | **59.7** | 1 |
| **S420** | **916** | **455** | **363** | **582** | **63.5** | 1 |
| **S444** | **888** | **474** | **388** | **509** | **57.3** | 1 |
| **S510** | **1020** | **564** | **441** | **597** | **58.5** | 1 |
| **S526** | **1052** | **555** | **474** | **588** | **55.9** | 2 |
| **S641** | **1278** | **467** | **421** | **898** | **70.3** | 2 |
| **S713** | **1426** | **581** | **519** | **961** | **67.4** | 1 |
| **S820** | **1640** | **850** | **702** | **975** | **59.5** | 2 |
| **S832** | **1664** | **870** | **718** | **983** | **59.1** | 2 |
| **S953** | **1906** | **1079** | **826** | **1116** | **58.6** | 2 |
| **S1196** | **2392** | **1242** | **964** | **1482** | **61.9** | 3 |
| **S1238** | **2476** | **1355** | **1035** | **1482** | **59.9** | 2 |
| **S1423** | **2846** | **1515** | **1214** | **1720** | **60.4** | 3 |
| **S1488** | **2976** | **1486** | **1110** | **1959** | **65.8** | 3 |
| **S1494** | **2988** | **1506** | **1123** | **1955** | **65.4** | 3 |
| **S5378** | **10590** | **4603** | **4034** | **6726** | **63.5** | 8 |
| **S9234** | **18468** | **6927** | **5753** | **13096** | **70.9** | 16 |
| **S13207** | **26358** | **9815** | **8346** | **18574** | **70.5** | 22 |
| **S15850** | **31694** | **11725** | **9564** | **22631** | **71.4** | 25 |
| **S35932** | **71224** | **39094** | **30117** | **41428** | **58.17** | 44 |
| **S38417** | **76678** | **31180** | **25818** | **51648** | **67.36** | 57 |
| **S38584** | **76864** | **-** | **-** | **49114** | **63.89** | 58 |

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