ABSTRACT

Context: Software development projects increasingly adopt unit testing as a way to identify and correct program faults early in the construction process. Code that is unit tested should therefore have fewer failures associated with it. 

Objective: Compare the number of field failures arising in unit tested code against those arising in code that has not been unit tested. 

Method: We retrieved 2083 979 crash incident reports associated with the Eclipse integrated development environment project, and processed them to obtain a set of 126 026 unique program failure stack traces associated with a specific popular release. We then ran the JaCoCo code test coverage analysis on the same release, obtaining results on the line, instruction, and branch-level coverage of 216 392 methods. We also extracted from the source code the classes that are linked to a corresponding test class so as to limit test code coverage results to 1 267 classes with actual tests. Finally, we correlated unit tests with failures at the level of 9 523 failing tested methods.

Results: Unit-tested code does not appear to be associated with fewer failures. 

Conclusion: Unit testing on its own may not be a sufficient method for preventing program failures.

CCS CONCEPTS

• Software and its engineering → Software testing and debugging. 

KEYWORDS

Unit-testing, crash incident reports, code coverage, stack traces, software reliability.

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Does Unit-Tested Code Crash? A Case Study of Eclipse

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1 INTRODUCTION

The rising size and complexity of software multiply the demands put on adequate software testing [25]. Consequently, software development projects increasingly adopt unit testing [6] or even test-driven development [5] as a way to identify and correct program faults early in the construction process. However, the development of testing code does not come for free. Researchers have identified that one of the key reasons for the limited adoption of test-driven development is the increased development time [7]. It is therefore natural to wonder whether the investment in testing a program’s code pays back through fewer faults or failures.

One can investigate the relationship between the software’s production code and its tests by utilizing heuristics or code coverage analysis [39]. Heuristics are based on conventions associated with the development of unit test code; for example that a test class is named after the class it tests (e.g. Employer), followed by the Test suffix (i.e. EmployerTest). Code coverage analysis is a process that provides metrics indicating to what extent code has been executed—under various control flow measures [4]. The corresponding metrics can be efficiently obtained through diverse tools [14, 36]. Then, the process for determining test coverage involves running the software’s test suite, and obtaining code coverage metrics, which in this case indicate code that (probably) is or (definitely) is not tested.

To examine how test code coverage relates to software quality, numerous methods can be employed. One can look at corrected faults and see whether the corresponding code was tested or not [24, 28]. In addition, faults can be deliberately introduced by mutating the code [20] in order to look at how test code coverage relates to test suite effectiveness [12, 17]. Alternatively, one can artificially vary test coverage to see its effect on exposing known faults [25]. Finally, one could look at software failures rather than faults and correlate these with test code coverage.

In this study we investigate the relationship between unit testing and failures by examining the usage of unit testing on code that is associated with failures in the field. We do this in three conceptual
steps. First, we run software tests under code coverage analysis to determine which methods have been unit tested and to what extent. We triangulate these results with heuristics regarding the naming of classes for which unit test code actually exists. Then, we analyze the stack traces associated with software failure reports to determine which methods were associated with a specific failure. Finally, we combine the two result sets and analyze how unit-tested methods relate to observed failures.

We frame our investigation in this context through the following research questions:

**RQ1** How does the testing of methods relate to observed failures?
**RQ2** Why do unit-tested methods fail?

A finding of fewer failures associated with tested code would support the theory that unit testing is effective in improving software reliability. Failing to see such a relationship would mean that further research is required in the areas of unit test effectiveness (why were specific faults not caught by unit tests) and test coverage analysis (how can coverage criteria be improved to expose untested faults).

The main contributions of our study are the following:

- A method for investigating the effectiveness of unit testing,
- an empirical evaluation between unit test coverage and failure reports, and
- an open science data set and replication package providing empirical backing and replicability for our findings.

In the following sections we describe the methods we used (Section 2), present our quantitative and qualitative results (Section 3), discuss their implications (Section 4), examine the threats to the validity of our findings (Section 5), outline related work in this area (Section 6), and conclude with a summary of our findings and their implications (Section 7).

## 2 METHODS

We based our study on the popular Eclipse open source integrated development environment [11]. In brief, to answer our research questions we obtained data regarding failures of the Eclipse IDE, we determined the most popular software version associated with the failures, we built this specific software version, we run the provided tests under a code coverage analysis tool, we combined the results with heuristics regarding the naming of test code, we joined the analyzed software failures with the corresponding code coverage analysis results, and we analyzed the results through statistics and a qualitative study. Following published recommendations [16], the code and data associated with this endeavor (AERI JSON data, code coverage analysis, stack traces analyzed, analysis scripts, and combined results) are openly available online.

In our presentation we use the following terms as defined in the systems and software engineering vocabulary standard [18].

- **Error** “Human action that produces an incorrect result.”
- **Fault** “Incorrect step, process, or data definition in a computer program,” “defect in a system or a representation of a system that if executed/activated could potentially result in an error.”

- **Failure** “Termination of the ability of a system to perform a required function or its inability to perform within previously specified limits; an externally visible deviation from the system’s specification.”

According to these definitions, a programmer error may result in a fault in the code. This may in turn cause a failure in the program’s operation, which may manifest itself as e.g. incorrect output, a program freeze, or an abnormal program termination; the last one often accompanied by a diagnostic report, such as a stack trace.

## 2.1 Data Provenance and Overview

We conducted our research on a dataset of anonymized diagnostic failure reports communicated to the Eclipse developers through the IDE’s Automated Error Reporting (AERI) system [3]. The AERI system is installed by default on the Eclipse IDE to aid support and bug resolution. Its back-end collects incidents, which contain data regarding a particular instance of an uncaught exception. It analyses them and aggregates similar ones into problems. The specific data set we used was generated on 2018-02-17 and contains data collected over the period 2016-03-13 to 2016-12-13. The dataset contains a file with the complete collected data and two extracts in CSV format containing a subset of fields and aggregate data. We based our study on the set titled “All Incidents”, which consists of 2 083 979 crash reports provided in the form of JSON files.

As subset of an AERI report in JSON format appears in Listing 1. The data attributes that are interesting for the purpose of our research are the following:

- **EclipseProduct**, the product associated with the Eclipse project,
- **Buildid**, the version of the Eclipse source code, and
- **Stacktrace**, the incident’s stack trace. Each stack trace consists of successive stack frames and their details (class, method, line).

To combine incident reports with the associated source code, compiled code, and test data, we decided to focus our study on a specific version of Eclipse. We therefore analyzed the AERI incident reports to find the Eclipse release associated with the highest number. This would allow us to obtain a large dataset for statistical analysis. Given that production releases are widely distributed, numerous failures associated with a release are a sign of the release’s popularity, rather than its inherent instability. An overview of the incidents associated with each release can be found in the AERI incidents analysis report [3, p. 18]. The data corresponding to the selected version consist of 126 026 incident files that have EclipseProduct equal to org.eclipse.epp.package.java.product and BuildID equal to 4.5.2.M20160212-1500.

## 2.2 Generation of Test Code Coverage Data

To create code coverage data associated with tests we needed to obtain the source code, compile it, and perform code coverage analysis while running the tests.

We accessed the Eclipse source code through the Eclipse Platform Releng project, which provides instructions for building the Eclipse Platform using preferred technologies identified as part

10.5281/zenodo.3610822

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1. Unpublished working draft. Not for distribution.
2. http://software-data.org/datasets/aeri-stacktraces/downloads/incidents_full.tar.bz2
3. https://wiki.eclipse.org/Platform-releng/Platform_Buil

2022-03-17 22:40. Page 2 of 1–12.
of the Eclipse Common Build Infrastructure (CBI) initiative. This combines infrastructure, technologies, and practices for building Eclipse software. To ensure that test coverage results would be coeval with the corresponding incident reports, we retrieved the source code version of Eclipse corresponding to the one whose stack traces we chose to analyze.

To obtain data regarding Eclipse’s test coverage, we used the JaCoCo Code Coverage [14] system, which is an open-source toolkit for measuring and reporting Java code coverage. It reports instruction, branch, line, method, class, package, and complexity coverage. Instruction is the smallest unit JaCoCo counts and is associated with single Java byte code instructions. Branch coverage reports the ratio of the executed cyclomatic complexity [27] graph paths over the total cyclomatic complexity number. Under line coverage, a source code line is considered to be covered if at least one instruction associated with the line has been executed. Finally, coverage of larger aggregates is reported on the basis of at least a single instruction. For the purposes of this study we focused on the most fine grained coverage metrics, namely line, instruction, and branch coverage.

Eclipse is a multi-module project, which hinders the derivation of code coverage reports, because the JaCoCo Maven goals used to work on single modules only. For that reason, we used the new “Maven Multi-Module Build” feature, which implements a Maven goal called “jacoco:report-aggregate”. This aggregates coverage data across Maven modules.

To apply this feature, we first added the JaCoCo plugin and profile in the Maven parent pom.xml file, and then we created a separate project where we:

- configured the report-aggregate goal,
- added as dependencies with scope compile the projects containing the actual code and with scopetest the projects containing the tests and the .exec-suffixed data.

Owing to the size and complexity of Eclipse, the process of compiling, testing, and obtaining code coverage results was far from trivial.

First, due to the fact that we run JaCoCo on an old (by about three years) release of Eclipse, it was difficult to make the code compile. The release comprised some repositories which had become archived at the time we attempted to build it, and therefore the specified path could not found. For example, in one case Maven terminated with an internal error reporting that it had failed to load to the repository eclipse-p2-repo from location http://download-1.evl.odeclipse.org/eclipse/updates/4.5-M-buils. To address this issue we replaced these repositories with newer ones.

Second, three tests remained stuck for more than one hour. One reason we might think this was happening was because the test was repeatedly trying to find a specific file. In the end we had to manually remove the offending tests in order to proceed with testing and code coverage analysis process.

Third, there were tests that needed specific configurations and data to run. Again, we had to skip those tests in order to allow the remaining ones to run.

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Listing 1: AERI incident data extract
These three problems resulted in a very time-consuming process, because every time a run failed, we had to fix and restart it to find the next missing repository or stuck test. The average time of each run was about three hours. In total we spent around three months fine-tuning the compilation process and the tests, until we were able to compile the project from source and run most of the tests to obtain test code coverage results.

2.3 Determination of Unit Test Classes

Code coverage data can be a notoriously fallacious measure of test quality [35]. Because good quality tests are associated with high code coverage and the absence of tests with low code coverage, many mistakenly think that high code coverage implies good quality testing. In fact, high code coverage can be achieved by having some code executed without testing its correct behavior. As an example the code for setting up a test case can invoke some class constructors, from the same or from another class, without however checking that the corresponding objects are correctly constructed.

To alleviate false positives regarding the existence of tests that would result from naively analyzing code coverage reports (class A got executed, therefore it is tested), we combined method-level code coverage data with data regarding the existence of classes containing unit tests.

Specifically, we found the classes of the source code that are relevant to a test class with the following procedure. A common unit test naming practice is to add the word 'Tests' in the end of the class name. However, that is not the case for the test methods (whose name may be quite different) and so we focused only on finding the unit-tests on class level.

Through manual examination of the source code we determined that Eclipse’s source code test files (classes) are usually named as follows.

1. ClassNameTests
2. ClassNameTest
3. TestClassName
4. Test_PackageName_ClassName
5. ClassNameTester

Another common unit test practice is to place test files under the tests/ folder with similar path as the class that they test. For example:

Bundle Class: eclipse.platform.ui/bundles/org.eclipse. eclips eupse.jface.databinding/src/org/eclipse/jface/datat etest;preferences/BooleanFieldEditorTests.java

Test Class: eclipse.platform.ui/tests/org.eclipse. eclips eupse.jface.databinding/src/org/eclipse/jface/datat etest;preferences/BooleanFieldEditorTest.java

We wrote a script to find the classes that have a corresponding unit test file by devising through successive experiments and implementing the following heuristics. For each sub-module we generated two sets: one of files containing in their name the word “test” and its complement. We then matched the two sets, by removing the word “test” from the filename and also by traversing the associated paths from the right to the left. In cases where this method failed, we matched files based on the number of same words in each path. In all cases but one we had one or more test files match a single class file. The cases where this relationship did not hold concerned the separate implementations of SWT for the Cocoa, GTK, and Win32 back-ends, which all shared the same test class eclipse.platform.swt/tests/org.eclipse.swt.test of some implementation.

We then matched files again, this time using the common code points of “tests” and its complement. We then matched the two sets, by removing the word “test” from the filename and also by traversing the associated paths from the right to the left. In cases where this method failed, we matched files based on the number of same words in each path. In all cases but one we had one or more test files match a single class file. The cases where this relationship did not hold concerned the separate implementations of SWT for the Cocoa, GTK, and Win32 back-ends, which all shared the same test class eclipse.platform.swt/tests/org.eclipse.swt.test of some implementation.

In addition, for each bundle class and each test class we counted the number of lines so as to see how well a class is tested (test density).

2.4 Data Synthesis

As a next step we combined the data elements derived in the preceding steps as follows.

1. Process the incident files of the dataset, extracting all methods from the stack traces together with their order of appearance. If a method appeared twice in the stack trace we kept only the very first appearance to avoid duplications.

2. Process the XML file generated by the JaCoCo coverage report (Section 2.2), extracting all methods together with their code coverage data.

3. Process the unit tests classes file and their line density generated with the method explained in Section 2.3.

4. Join the common methods of the three preceding lists into a new list containing the combined fields.

The resulting output and its description are provided in the paper’s replication package.
Table 1: Code Coverage of Methods with Class Unit Tests

|                  | Covered | Class Unit Test |
|------------------|---------|-----------------|
|                  | No      | Yes             |
| No               | 3115    | 366             |
|                  | (32.7%) | (3.8%)          |
| Yes              | 4890    | 1152            |
|                  | (51.3%) | (12.1%)         |
| Total            | 8005    | 1518            |
|                  | (84.1%) | (15.9%)         |

Following the methods we described in Section 2.4, we matched 14 902 crash methods with their test coverage details. Since faulty methods in a stack trace appear mostly, within the top-10 stack frames [34], we excluded the methods that appeared after the 10th stack frame and kept 9 523 crash methods.

Of those 9 523 crash methods, the 6 042 (63%) are covered according to JaCoCo (instruction% > 0). In terms of branches they are covered by 55%, in terms of instructions by 58% and in terms of lines, by 59%. Also, 1 518 (16%) methods out of 9 523 belong to a class with unit test, with average code coverage line density of 71%. The number of methods that belong to a class with unit test and have also non-zero code coverage percentage, is 1 152.

We decided to focus only on the methods appearing in the stack trace’s top position, because a) the method at the stack’s top, as the one where the exception occurred, is certainly implicated in the crash, even if it may not be the crash’s root cause; and b) 40% of bugs are fixed in the very first frame [34]. The number of crash methods that satisfy this criterion, is 1 166 methods out of the 9 523 (12%).

Drilling further in the association between code coverage and crashes, we examined the relationship between the covered methods, methods of unit-tested classes, and methods of the topmost stack frame. Among 1 166 methods associated with failures, test code coverage and the existence of unit tests within the class are related as depicted in Figure 1 and summarized in Table 1. The numbers we obtained indicate that code coverage on its own cannot be used as a reliable indicator for determining the existence of unit tests. Consequently, we decided to consider as unit tested methods those whose code is covered during testing and whose class has a corresponding one with unit tests.

2.6 Preliminary Qualitative Analysis

We conducted a qualitative study of our data so as to gain a better insight of the crashes, the tests, and the code coverage results.

As expected, in the JaCoCo results found methods with code coverage higher than 0 but no tests for their methods. The reason for this is because JaCoCo in common with other code coverage tools shows which instructions, lines, or branches of the code were (or were not) executed when running the tests. This however does not mean that a given method was tested, because its code might have been called by another method’s test. Below we outline specific cases of test coverage we related with the existence of actual test code, as outlined in Section 2.3.

1. Methods of classes with unit tests and zero code coverage. There are methods with zero code coverage percentage (according to the JaCoCo results) that belong to a class that is associated with a test code line density ratio of 67% and a median test code line density across methods of 71%.

We see that only 12% (1 267/10 513) of the JaCoCo covered classes belong to unit-tested classes. This small number is justified by the fact that JaCoCo shows which code was executed (or not) when running tests. The coverage does not necessarily mean that a given class was tested, because its code might have been called from other code.

The position of faulty methods in a stack trace was examined by Schroter and his colleagues [34]. They studied 2 321 bugs from the Eclipse project, and examined where defects were located in stack traces as defined by the corresponding fix. Their research showed that 40% of bugs were fixed in the very first frame, 80% of bugs were fixed within the top-6 stack frames, and 90% of bugs were fixed within the top-10 stack frames. We correspondingly grouped and matched methods appearing in stack traces into three groups of methods: those that have appeared at least once in the very first, in the top-6, and in the top-10 stack frames.
class found through the heuristics outlined in Section 2.3. Since it does not make much sense to have unit tests that are not executed, we investigated this further to see why that happens. The main reason seems to be wrong results from JaCoCo, which skipped some tests that were not running due to configuration settings. For example, most of the tests of the module rt.equinox.p2 did not run successfully and so most of its classes and methods got a zero coverage percentage, although they had unit tests. Specifically, the class org.eclipse.equinox.internal.p2.metadata.repository.CompositeMetadataRepository is related to the unit-test class org.eclipse.equinox.p2.tests.metadata.repository.y.CompositeMetadataRepositoryTest which tests some of its methods, but JaCoCo indicated zero coverage for its methods such as the method addChild. Interestingly, this method also appeared on the topmost stack frame of 50 incident reports.

Another case occurs when the test class contains tests for a subset of the class’s methods and none of the other unit tests or unit-tested methods execute some methods. This results in JaCoCo indicating no coverage for some methods. Thus the presence of unit tests for a class is no guarantee for unit tests for all the class’s methods. We found for example this to be the case in the method doSetValue(Object source, Object value) of the class org.eclipse.core.internal.resources.Workspace.

Despite its intuitive justification, this is not a common phenomenon: only 336 methods of those listed in incident stack traces out a total of 9,523 belong to this category.

2. Methods of classes without unit tests and non-zero code coverage. This category comprises methods with a non-zero coverage percentage that do not belong to any of the classes with unit test found through the procedure described in section 2.3. This is an extension of the case where methods have their code covered, even though they have no tests associated with them. Unsurprisingly, we found 4,890 methods out of 9,523 belonging to this category, because many methods delegate some work to others.

3. Methods of classes with unit tests and non-zero code coverage. This category comprises methods that not only have a non-zero code coverage percentage (according to JaCoCo), but also belong to a class with unit-test code. There are 1,152 methods belonging to this category (see Section 2.5). These two conditions provide the greatest assurance that a method is indeed covered by a test. In practice, we found two cases:

1. methods having non-zero code coverage and a test class but no unit test for the specific method, and
2. methods having non-zero code coverage and a test class with a unit test, which can fully or partially cover the specific method.

An example of the first case can be found in method delete(int updateFlags, IProgressMonitor monitor) of the class org.eclipse.compare.tests.CompareUIPluginTest, which tests the method.

Listing 2: Code of partially covered method

```
public ViewerDescriptor[]
    findContentViewerDescriptor(Viewer oldViewer, Object in, CompareConfiguration cc) {
    Set result = new LinkedHashSet<>();
    if (in instanceof IStreamContentAccessor) {
        String type= ITypedElement.TEXT_TYPE;
        if (in instanceof ITypedElement) {
            ITypedElement tin= (ITypedElement) in;
            IContentType ct= getContentType(tin);
            initializeRegistries();
            List list = fContentViewers.searchAll(ct);
            if (list != null)
                result.addAll(list);
        }
        String ty= tin.getType();
        if (in instanceof IStreamContentAccessor) {
            IStreamContentAccessor contentViewerDescriptor=
                (IStreamContentAccessor) in;
            if (ct != null) {
                initializeRegistries();
                List list = fContentViewers.searchAll(ct);
                if (list != null)
                    result.addAll(list);
            }
            if (ty != null)
                type= ty;
        }
    }
    return result;
}
```

A representative example of the second case is the fully covered method getAllSupertypes0 of the class org.eclipse.jdt.core.internal.core.hierarchy.TypeHierarchy. The corresponding test class org.eclipse.jdt.core.tests.model.TypeHierarchyTest contains the method testGetAllSupertypes, which tests the method.

An example of a partially covered method is the method findContentViewerDescriptor of the class org.eclipse.compare.compareUIPlugin which is covered by 50% on instruction level and 35% by branch coverage. The corresponding test class is the org.eclipse.compare.compareUIPluginTest and it contains the methods testFindContentViewerDescriptor and testFindContentViewerDescriptor.ForTextType_StreamAccessor, which tests the method.

4. Non-faulty methods in incident stack traces. We noticed that there are numerous methods that appear in many incident stack traces, although they have unit tests associated with them and appear to be correct. This raises the question of how could a method appearing in so many incident reports not have been noticed and fixed by the developers.

One answer is that many of those methods are used for either debugging (such as reporting exceptions, log specific messages, handle assertions, check if something exists or is null) or for triggering code (such as run(), invoke(), execute()) and are therefore not directly associated a fault.
public void testFindContentViewerDescriptor() {
    CompareConfiguration cc = new CompareConfiguration();
    DiffNode in = new DiffNode(new TextTypedElementStreamAccessor(), new TextTypedElementStreamAccessor());
    ViewerDescriptor[] result = CompareUIPlugin.getDefault().findContentViewerDescriptor(null, in, cc);
    assertNotNull(result);
    assertEquals(1, result.length);
}

Listing 3: Test class of partially covered method

public class SecurePreferences {
    [...] 
    protected SecurePreferencesRoot getRoot() {
        if (root == null) {
            SecurePreferences result = this;
            while (result.parent() != null) { 
                result = result.parent();
                root = (SecurePreferencesRoot) result;
            }
            return root;
        }
        [...] 
    public SecurePreferences parent() {
        checkRemoved();
        return parent;
    }
    [...] 
    private void checkRemoved() {
        if (removed) 
            throw new IllegalStateException(NLS.bind (SecAuthMessages.removedNode, name));
    }
    [...] 
}

Listing 4: Faulty method's call chain code

The debugging methods are usually found at the first stack frame of the stack trace, and the triggering methods within the top-6 and top-10 frames. For example method run(IWorkspaceRunnable, IProgressMonitor) of class org.eclipse.core.internal.resources.Workspace appeared in 4293 stack traces (such as incident_360023.json) at the top-6 frames and method checkExists of class org.eclipse.core.internal.resources.Resource appeared in 2020 stack traces (such as incident_1655649.json), with average length of 25 frames. The position of faulty methods in a stack trace can be found in one of the top-10 stack frames according to Schroter and his colleagues [34], which mean that one of the last 10 methods that were called are likely to contain the defect.

As described in Section 2.6, there are many methods appearing at top-6 and top-10 positions (excluding the topmost position) that are not related to the crash. Along with the fact that the exception occurred in the first stack frame, we consider the first (topmost) frame in the stack as the method that caused the crash, and thus we decided to strictly define a method as associated with the crash when it appears in the stack trace’s top position.

2.7 Statistical Analysis and Methods

A typical Java stack trace is a list of the method calls or stack frames that the application was in the middle of before an error or exception was thrown (or generated manually). A stack trace can range from a single stack frame (e.g stack trace of file incident_627736.json) to 1024 frames (e.g stack trace of file incident_1655649.json), with average length of 25 frames. The position of faulty methods in a stack trace can be found in one of the top-10 stack frames according to Schrotter and his colleagues [34], which mean that one of the last 10 methods that were called are likely to contain the defect.

When the program started, the Java runtime executed the run() method. The run() method called getRoot and getRoot called parent, which called checkRemoved. Finally, checkRemoved threw IllegalStateException, which generated the stack trace.
To answer RQ1 regarding the association between unit tests and crashes, we test the alternative hypothesis in the statistical analysis environment \([15, 32]\) as Fisher’s exact test for count data \([9, 10]\), which is available on the R statistical analysis environment [15, 32] as fisher.test. As we are only interested on whether testing is associated with fewer crashes (and not the reverse of whether fewer crashes are associated with testing) we test the alternative hypothesis in the less direction.

### 3 RESULTS

Here we answer our two research questions by means of statistical (RQ1) and qualitative (RQ2) analysis.

#### 3.1 Statistical Analysis

To answer RQ1 regarding the association between unit tests and crashes we classified the 9 523 methods as unit tested and crashed according to the criteria we specified in Section 2.7. This resulted in their categorization depicted in Figure 3 and summarized in Table 2.

Our question is whether testing a piece of code is associated with a lower chance of it crashing. Applying Fisher’s exact test for count data, results in a \(p\)-value of 0.278 and an odds ratio based on the conditional maximum likelihood estimate of 0.915 in a 95% confidence interval of \(0–1.146\). Consequently, we cannot reject the null hypothesis, and conclude that our data set does not provide statistical evidence supporting the hypothesis that the presence of unit tests is associated with fewer crash incidents.

#### 3.2 Qualitative Analysis

To answer RQ2 on why do unit-tested methods still fail, we analyzed the 67 methods that are strictly unit-tested and crashed. This may sound like a small number, but those methods appeared in 10 608 stack traces.

By examining the stack traces and their relevant methods in the Eclipse source code, we classified crashes of unit tested methods into three categories.

1. **The method contains a developer-introduced fault.** These faults stem from programmer errors, such as algorithmic, logic, ordering, dependency, or consistency errors [23]. They mainly involve code parts that are missing error-handling mechanisms for code that can potentially throw exceptions, thus causing the application to crash with an uncaught exception error.

   An example of a method belonging to this category, is getPath of class org.eclipse.jdt.internal.core.search.JavaSearch← Scope.java (Listing 6). This was found to be the topmost method in 12 stack traces, such as incident_69854.json. The stack trace indicated that the crash occurred on line 2 which makes sense, because a NullPointerException can be thrown at that point if element is null.

   This method belongs to the category 3.1 we presented in Section 2.6. It has been called by multiple other tested methods providing different element input, without testing it with a null argument. If developers had written a test that specifically checked this method, they might have covered this case.

   Another example is the method consumeEmptyStatement (Listing 7). This was found to be the topmost method in 11 stack traces such as incident_1324714.json of class org.eclipse.jdt← internal.compiler.parser.Parser. It seems to cause an IOException on line 3.

2. **The method intentionally raises an exception.** There are methods that intentionally lead to crashes due to internal errors, wrong configuration settings, or unanticipated user behavior, rather than

![Figure 3: Relationship between strictly tested and strictly crashed methods. The pie areas correspond to the colored areas of the Venn diagram.](image)

| Table 2: Crashes of Tested Methods |
|-----------------------------------|
| Crashed | Unit tested | Total |
|---------|-------------|-------|
| No      | 7835 (82.3%) | 589 (6.2%) | 8934 (93.8%) |
| Yes     | 1099 (11.5%) | 67 (0.7%) | 1166 (12.2%) |

In addition, on our preliminary qualitative analysis, we considered a method as unit-tested in one of the following cases:

1. Method belongs to a unit-tested class but has no JaCoCo coverage data.
2. Method does not belong to a unit-tested class but has JaCoCo coverage data.
3. Method belongs to a unit-tested class and has JaCoCo coverage data.

We decided to consider a method as unit tested by keeping only the methods that belong to a unit-tested class and have JaCoCo line code coverage more than the median of the non-zero covered lines percentages, namely 98.3%.

Based on these two definitions we generate a \(2 \times 2\) contingency table containing the multivariate frequency distribution of the two variables: tested, crashed. We can then test for statistical significance (deviation from the null hypothesis of RQ1) by applying statistical evidence supporting the hypothesis that the presence of unit tests is associated with fewer crash incidents.
5
{
  char[] source = this.scanner.source;
  if (source[this.endStatementPosition] == ';') {
    pushOnAstStack(new EmptyStatement
      (this.endStatementPosition,
       this.endStatementPosition));
  } else {

Listing 7: Example of a faulty method caused by a developer error regarding array indexing

private void checkRemoved() {
  if (removed)
    throw new IllegalStateException(NLS.bind
      (SecAuthMessages.
       removeNode, name));
}

Listing 8: Example method of an internal error

private void fail(String message) throws TemplateException {
  fErrorMessage= message;
  throw new TemplateException(message);
}

Listing 9: Example of a non-faulty method

faults introduced through a developer oversight. Developers understood that these failures could potentially happen under unforeseen circumstances or in ways that could not be appropriately handled. As a backstop measure they intentionally throw exceptions with appropriate messages in order to log the failure and collect data that might help them to correct it in the future.

We found for example this to be the case in stack trace incide→ent_2029150.json in which the first frame contains the method checkRemoved (Figure 8) of class org.eclipse.equinox.inter→nal.security.storage.SecurePreferences, which throws an IllegalStateException and logs the message “Preference node 'name' has been removed”.

3. The method is not faulty. There are methods in the topmost stack position that simply report a failure associated with a fault in another method. These methods are the non-faulty (debugging) methods we described in category 4 of Section 2.6. An example of such a case is method fail of the class org.eclipse.jface.t→ext.templates.TemplateTranslator (Figure 9).

Having analyzed the crashes, we worked on understanding why those crashes occurred while there was (apparently) unit tested code. Unit testing would not help alleviate cases 2 and 3, and therefore we did not investigate further. On the other hand, methods belonging to the first case are much more interesting, so we dug deeper to understand the types of faults, failures, and their relationship to unit testing, and categorized them into the following areas.

1.a Method is not called by the class’ tests. The method’s test class does not call the specific method in any of the tests. The method may have been incidentally called by tests of other classes. We found for example this to be the case in method resetProcessChangeSt→ate of class org.eclipse.text.undo.DocumentUndoManager.

1.b Method is not tested by the class’ tests. The method’s test class calls this method to setup or validate other tests, but does not explicitly test the given method. We found for example this to be the case in method getPath (Listing 6) we previously saw on this section on paragraph 1. Similarly, there are many such tests in test class org.eclipse.jdt.core.tests.compiler.parser.Pars←erTest or org.eclipse.core.tests.resources.ResourceT←est.

1.c Specific case is not tested. The method has a unit test, but some specific cases are not tested. Ideally, all cases should be tested to ensure that the discrete unit of functionality performs as specified under all circumstances. An example of this case is the partially (90%) covered method iterate of the class org.eclipse.eclips←e.core.internal.watson.ElementTreeIterator with unit test class org.eclipse.core.tests.internal.watson.ElementT←reeIteratorTest. This method causes an IndexOutofBounds Ex→ception, but the test method does not test this case.

4 DISCUSSION

In isolation and at first glance, the results we obtained are startling. It seems that unit tested code is not significantly less likely to be involved in crashes. However, one should keep in mind that absence of evidence is not evidence of absence. We have definitely shown that unit tests fail to reduce crashes.

Regarding the result, we should remember that our data come from a production-quality widely used version of Eclipse. It is possible and quite likely that the numerous faults resulting in failures were found through the unit tests we tallied in earlier development, alpha-testing, beta-testing, and production releases. As a result, the tests served their purpose by the time the particular version got released, eliminating faults whose failures do not appear in our data set.

Building on this, we must appreciate that not all methods are unit tested and not all methods are unit tested with the same thoroughness. Figure 1 shows that fewer than half of the methods and lines are unit tested. Furthermore, Figure 2 shows that code coverage within a method’s body also varies a lot. This may mean that developers selectively apply unit testing mostly in areas of the code where they believe it is required.

Consequently, an explanation for our results can be that unit tests are preferentially added in complex and fault-prone code in order to weed out implementation bugs. Due to its complexity, such code is likely to contain further undetected faults, which are in turn likely to be involved in field failures manifesting themselves as reported crashes.

One may still wonder how can unit-tested methods with a 100% code coverage be involved in crashes. Apart from the reasons we identified in Section 3.2, one must appreciate that test coverage is a complex and elusive concept. Test coverage metrics involve statements, decision-to-decision paths (predicate outcomes), predicate-to-predicate outcomes, loops, dependent path pairs, multiple conditions, loop repetitions, and execution paths [21, pp. 142–145], [4]. In contrast, JaCoCo analyses coverage at the level of instructions, lines, and branches. While this functionality is impressive by industry standards, predicate outcome coverage can catch only about 85% of revealed faults [21, p. 143]. It is therefore not surprising that failures still occur in unit tested code.
An important factor associated with our results is that failures manifested themselves exclusively through exceptions. Given that we examined failure incidents through Java stack traces, the fault reporting mechanism is unhandled Java exceptions. By the definition of an unhandled exception stack trace, all methods appearing in our data set passed an exception through them without handling it internally. This is important, for two reasons. First, unit tests rarely examine a method’s exception processing; they typically do so only when the method under test is explicitly raising or handling exceptions. Second, most test coverage analysis tools fail to report coverage of exception handling, which offers an additional, inconspicuous, branching path.

It would be imprudent to use our findings as an excuse to avoid unit testing. Instead, practitioners should note that unit testing on its own is not enough to guarantee a high level of software reliability. In addition, tool builders can improve test coverage analysis systems to examine and report exception handling. Finally, researchers can further build on our results to recommend efficient testing methods that can catch the faults that appeared in unit tested code and test coverage analysis processes to pinpoint corresponding risks.

5 THREATS TO VALIDITY

Regarding external validity, the generalizability of our findings is threatened by our choice of the analyzed project. Although Eclipse is a very large and sophisticated project, serving many different application areas, we cannot claim that our choice represents adequately all software development. For example, our findings may not be applicable to small software projects, projects in other application domains, software written in other programming languages, or multi-language projects. Finally, we cannot exclude the possibility that the selection of a specific Eclipse product and release may have biased our results. If anything, we believe additional research should look at failures associated with less mature releases.

Regarding internal validity we see four potential problems. First, the code coverage metrics we employed have room for improvement, by incorporating e.g. branch coverage or mutation testing data. Second, employing JaCoCo on an old release which may have some deprecated code and archived repos, caused some unit test failures, resulting in a lower code coverage. Third, we excluded from the JaCoCo report non-Java code that is processor architecture specific (e.g. org.eclipse.core.filesystem.linux.x86 bundle). Fourth, noise in some meaningless stack frames appearing in our stack trace dataset may have biased the results.

6 RELATED WORK

Among past studies researching the relationship between unit test coverage and software defects, the most related to our work are the ones that examine actual software faults. Surprisingly, these studies do not reach a widespread agreement when it comes to the relationship between the two. More specifically existing findings diverge regarding the hypothesis that a high test coverage leads to fewer defects. Mockus et al. [28], who studied two different industrial software products, agreed with the hypothesis and concluded that code coverage has a negative correlation with the number of defects. On the other hand, Gren and Antinayan’s work [13] suggests that unit testing coverage is not related to fewer defects and there is no strong relationship between unit testing and code quality. A more recent study by the same primary author [2], investigated an industrial software product, and also found a negligible decrease in defects when coverage increases, concluding that test unit coverage is not a useful metric for test effectiveness.

Furthermore, in a study of seven Java open source projects, Petric et al. found that the majority of methods with defects had not been covered by unit tests [31], deducing that the absence of unit tests is risky and can lead to failures. On the other hand, Kochhar et al. in another study of one hundred Java projects, did not find a significant correlation between code coverage and defects [24].

The above-mentioned studies cover only fixed faults. In our research, we work with stack traces, which enable us to analyze field-reported failures associated with crashes. The associated faults include those that have not been fixed, but exclude other faults that are not associated with crashes, such as divergence from the expected functionality or program freezes. Furthermore, through the crash reports we were unable to know the faulty method associated with the crash. However, by placing our matched crash methods in three groups according to their respective position in the stack trace (in the very first stack frame, within the top-6 and the top-10 stack frames) we could obtain useful bounds backed by empirical evidence [34] regarding the coverage of methods that were likely to be defective.

Considerable research associating testing with defects has been performed on the relationship between test-driven development and software defects. Test-driven development (TDD) is centered around rapid iterations of writing test cases for specifications and then the corresponding code [5]. As a practice it obviously entails more than implementing unit tests, but absence of evidence of TDD benefits should also translate to corresponding absence of benefits through simple unit testing, though the benefits of TDD will not necessarily translate into benefits of unit testing. In a review of the industryâ€”Zs and academiaâ€”Zs empirical studies, MÃ¼nch and MÃ¼nch [26] found that TDD has positive effects in the reduction of defects a result also mirrored in an earlier meta-analysis [33] and a contemporary viewpoint [29]. In industry, an IBM case study found that test-driven development led to 40% fewer defects [38]. In academia, classroom experiment results showed that students produce code with 45% fewer defects using TDD [8]. On the other hand, experimental results by Wikerson and Mercer failed to show significant positive effects [37].

The study by Jia and Harman [19] shows clear evidence that mutation testing has gained a lot popularity during the past years. The majority of researchers concluded that high mutation score improves fault detection [30]. Furthermore, mutation testing can reveal additional defect cases beyond real faults [1]. However, mutants can only be considered substitute of real faults under specific circumstances [22].

Apart from Schroter and his colleagues [34], a number of researchers have studied the Eclipse IDE and most of them have focused on predicting defects. Most notably, Zimmermann and his colleagues provided a dataset mapping defects from the Eclipse database to specific source code locations annotated with common complexity metrics [41], while Zhang [40] based on Eclipse data, yet again, suggested lines of code as a simple but good predictor of defects.
7 CONCLUSIONS

Software testing contributes to code quality assurance and helps developers detect and correct program defects and prevent failures. Being an important and expensive software process activity it has to be efficient. In our empirical study on the Eclipse project we used the JaCoCo tool and a class source code matching procedure to measure the test coverage, and we analyzed field failure stack traces to assess the effectiveness of testing. Our results indicate that unit testing on its own may not be a sufficient method for preventing program failures. Many methods that were covered by unit tests were involved in crashes, which may mean that the corresponding unit tests were not sufficient for uncovering the corresponding faults. However, it is worth keeping in mind that failures manifested themselves through exceptions whose branch coverage JaCoCo is not reporting. Research building on ours can profitably study the faults that led to the failures we examined in order to propose how unit testing can be improved to uncover them, and how test coverage analysis can be extended to suggest these tests.

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