Revisiting W1 Indications

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MISSION IMPOSSIBLE
Revisiting W1 Indications

How W1s mislead many in the aftermath of Northridge…
…and continue to do so today.
Revisiting W1 Indications

W1s: What Are They?
Figure 2b. Survey form Section V damage types.
Figure 2b. Survey form Section V damage types.
Figure 2c. Form Section V damage types, continued.
Figure 2c. Form Section V damage types, continued.
Figure 2a. Survey form Section V damage description page.

**Flange**
- **W1**: Incipient weld crack
- **W2**: Full or partial crack through weld metal
- **W3**: Fracture at girder interface
- **W4**: Fracture at column interface

**Weld**
- **W1**: Incipient weld crack
- **W2**: Full or partial crack through weld metal
- **W3**: Fracture at girder interface
- **W4**: Fracture at column interface

**Damage**
- **C3**: Lamellar flange crack
- **S1**: Weld crack at column (welded web only)
- **S2**: Weld crack at shear tab
- **S3**: Crack in girder web or shear plate through bolt holes
- **S4**: Plastic deformation of web or plate at bolt holes
- **S5**: Loose, damaged, or missing bolts
- **P1**: Damage to continuity plate
- **P2**: Crack in continuity plate weld
- **P3**: Damage to doubler plate
- **P4**: Crack in doubler plate weld
- **P5**: Partial depth crack in column web (extension of C3)
- **P6**: Full (or near full) depth crack in column web

Provide additional descriptions of MRF joint damage as appropriate:
W1  Incipient weld crack
Examination of a few damaged welds reveals that only half of the bottom flange has cracked. In addition, some welds appear to have been cracked prior to the earthquake. These cracks have been identified through the presence of rust in the weld crack.
SUMMARY REPORT

Appropriate action must be taken to improve the observed performance, especially wherein a high 60-80% connection failure rate occurred in some moment frames.
Revisiting W1 Indications

W1s: What Caused Them? (early thoughts)
Invitational Workshop on Steel Seismic Issues
Los Angeles, CA
September 8-9, 1994
SAC 94-01
WELDING AND MECHANICAL PROPERTIES OF WELDS

Preheat, Cooling Rates and Postheat

It was noted that evidence of pre-existing cracks, especially in the root of the welds, had been detected in many of the damaged SMRF connections. This could have easily been the result of inadequate preheat.
It was acknowledged that structural steel erectors do not closely adhere to good preheat practices, and that increased monitoring to ensure minimum uniform preheats are properly applied is imperative.
WELDING AND MECHANICAL PROPERTIES OF WELDS

Preheat, Cooling Rates and Postheat

It was suggested that hardness in the Heat Affected Zone (HAZ) could have played a significant role in the failure mechanism of weld in the Northridge earthquake. High hardness could have reduced toughness, increased a hydrogen embrittlement problem, and reduce ductility of the HAZ.
WELDING AND MECHANICAL PROPERTIES OF WELDS

Preheat, Cooling Rates and Postheat

For repair work, it was agreed that an increase of 100 degrees Fahrenheit above the minimum required preheat temperature required by AWS D1.1 for a given material and thickness should be adopted as an inexpensive way to mitigate the initiation of cracking during the repair of damaged SMRF connections.
WELDING AND MECHANICAL PROPERTIES OF WELDS

Preheat, Cooling Rates and Postheat

Slow cooling with insulating blankets was considered to be worthwhile to diffuse hydrogen.
WELDING AND MECHANICAL PROPERTIES OF WELDS

Preheat, Cooling Rates and Postheat

The use of Dehydrogenation Heat Treat (DHT) for thicker joints was considered to be worthwhile, and a recommendation was made to use 450 degrees Fahrenheit for one hour per inch of thickness, when the weld joint exceeds 1”.
WELDING AND MECHANICAL PROPERTIES OF WELDS

Welding Electrodes

It was agreed that the SMAW E7018 low hydrogen electrode was the most reliable and exhibited the best properties under field conditions.
SURVEY OF DAMAGE—Preliminary Report

Background

As of September 1994, eight months after the earthquake, the estimate has grown to over 100 damaged MRF buildings....
THE SAC STEEL PROGRAM
The Problem

Among the many issues discussed...there are six main problems most often put forth:

• Inadequately executed welds
• Pre-existent cracks in the weldments
• Residual stresses in the joint resulting from the welding and construction process
• Use of inappropriate weld material, preparation, process and heat treatment
• Through-thickness tension failure of the column flanges
• Fundamental problems with the joint configuration.
Revisiting W1 Indications

W1s: How Were They Detected?
Difficult to distinguish with UT between an acceptable weld with backing left in place and a weld with a root crack.
Impossible to distinguish with UT whether a crack is pre-existing, or due to earthquake.
Good weld
Crack in weld
Crack in fusion zone
Crack in HAZ
Incomplete fusion
Lamellar tear
Crack in weld

Crack in fusion zone

Crack in HAZ

Incomplete fusion

Lamellar tear

Good weld

All could be identified as W1 in inspection reports
The solutions to these problems are very different.
Revisiting W1 Indications

W1s: Did They Cause the Northridge Fractures?
FEMA 267

Interim Guidelines: Evaluation, Repair, Modification and Design of Welded Steel Moment Frame Structures

August 1995
INTRODUCTION
Background

Investigators initially identified a number of factors which may have contributed to the initiation of fractures at the weld root including: notch effects created by the backing bar…substandard welding…and potentially, pre-earthquake fractures resulting from initial shrinkage of the highly restrained weld during cool-down.
Such problems could be minimized in future construction, with the application of appropriate welding procedures and more careful exercise of quality control during the construction process. However, it is now known that these were not the only cause of the fractures which occurred.
Type W1 is the single most commonly reported non-conforming condition, representing more than 80 per cent of the total damage reported.
Figure 3-4  Types of Weld Damage
Table 3-4  Types of Weld Damage, Defects and Discontinuities

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>Weld root indications</td>
</tr>
<tr>
<td>W1a</td>
<td>Incipient indications – depth, 3/16” or t_f/4; width &lt; b_f/4</td>
</tr>
<tr>
<td>W1b</td>
<td>Root indications larger than that for W1a</td>
</tr>
<tr>
<td>W2</td>
<td>Crack through weld metal thickness</td>
</tr>
<tr>
<td>W3</td>
<td>Fracture at column interface</td>
</tr>
<tr>
<td>W4</td>
<td>Fracture at girder flange interface</td>
</tr>
<tr>
<td>W5</td>
<td>UT detectable indication – non-rejectable</td>
</tr>
</tbody>
</table>
Some engineers believe that type W1a indications are not earthquake damage at all, but rather, previously undetected defects from the original construction process. A W1b indication is one that exceeds these limits but is not clearly characterized by one of the other types. It is more likely that W1b indications are the result of the earthquake than the construction process.
Some engineers, with knowledge of fracture mechanics, have suggested if materials with adequate toughness are used, and welding procedures are carefully specified and followed, adequate reliability can be obtained from the traditional connection details.
INTRODUCTION

Background

Others believe that the conditions of high tri-axial restraint present in the beam flange to column flange joint (Blodgett—1995) would further prevent ductile behavior of these joints regardless of the procedure used to make the welds. Further they point to the important influence of the relative yield and tensile strength of beam and column materials, and other variables that can affect connection behavior.
INTRODUCTION

Background

To date, there has not been sufficient research conducted to resolve this issue.
Revisiting W1 Indications

W1s: What Did The SAC Investigations Learn About Them?
CONCLUSIONS
CONCLUSIONS

1. W1’s are a result of poor welding and inspection practices during construction, not a result of earthquake ground motions.
CONCLUSIONS

2. Ultrasonic inspection as normally employed by testing laboratory personnel is not a reliable inspection technique for identifying defects in the roots of welded full penetration “T” joints with backing.
Difficult to distinguish with UT between an acceptable weld with backing left in place and a weld with a root crack.
“Ultrasonic Inspection...is not a reliable inspection technique for identifying defects in the roots of welded full penetration “T” joints with backing.”
CONCLUSIONS

3. The extent of earthquake damage to WSMF buildings is substantially less than has previously been reported.
However, assorted anecdotal evidence suggested that W1’s might not be earthquake related at all. For example, a number of samples of W1b’s trepanned from welded connections and examined in the laboratory were determined to contain only areas of nonfusion and slag, without any crack extension or other potentially earthquake-related conditions.
Clarifying the Extent of Northridge-Induced Weld Fracturing; Examining the Related Issue of UT Reliability

Figure 6: Distribution of W1’s and non-W1’s in City of Los Angeles Inventory
Clarifying the Extent of Northridge-Induced Weld Fracturing; Examining the Related Issue of UT Reliability

Figure 6  Distribution of W1’s and non-W1’s in City of Los Angeles Inventory

- **W1 only**: 34% of 71 buildings
- **Non-W1 >10%**: 11% of 24 buildings
- **Non-W1 <10%**: 23% of 48 buildings
- **No W1 or non-W1**: 32% of 66 buildings

> 100 damaged buildings

2/3rds of building = damaged
Clarifying the Extent of Northridge-Induced Weld Fracturing; Examining the Related Issue of UT Reliability

Figure 6  Distribution of W1’s and non-W1’s in City of Los Angeles Inventory

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- No W1 or non-W1: 32%
- Non-W1 <10%: 23%
- Non-W1 >10%: 11%

- 71 buildings
- 48 buildings
- 24 buildings
- < 100 damaged buildings

1/3rds of building = damaged
Figure 1. Polished and Etched Weld Sample with W1

From SAC/BD-99/10
Clarifying the Extent of Northridge-Induced Weld Fracturing; Examining the Related Issue of UT Reliability

Figure 2. Location most often defined for W1’s by ultrasonics

“…only areas of nonfusion and slag, without any crack extension…”
Clarifying the Extent of Northridge-Induced Weld Fracturing; Examining the Related Issue of UT Reliability

Figure 7. Cumulative Occurrence of Non-W1’s in City of Los Angeles Inventory
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90% of all non-W1 damage in 27 buildings
Figure 7. Cumulative Occurrence of Non-W1’s in City of Los Angeles Inventory

Cumulative Damage

80% of all non-W1 damage in 16 (±) buildings
Figure 7. Cumulative Occurrence of Non-W1’s in City of Los Angeles Inventory

- 60% of all non-W1 damage in 4 (±) buildings

Cumulative Damage

% of all connections with non-W1s

40%

0%

Building, ranked in increasing # of non-W1s
Figure 7. Cumulative Occurrence of Non-W1’s in City of Los Angeles Inventory

Caveat:
These data are based on LA inventory of inspected buildings.
Clarifying the Extent of Northridge-Induced Weld Fracturing; Examining the Related Issue of UT Reliability

Figure 6  Distribution of W1’s and non-W1’s in City of Los Angeles Inventory

CAVEAT: These data are based on LA inventory of inspected buildings.

General ratios might apply (1/3rd-1/3rd-1/3rd)

Building numbers do not apply outside data base
Therefore, in the general region of strongest ground shaking only 24 buildings (11% of the total sample) were found to have more than 10% of their connections damaged by the earthquake. The scope of the “welded moment frame problem”—previously characterized as having results in many scores of severely damaged buildings—appears to be greatly reduced.”
Revisiting W1 Indications

W1s: What Was Done To Eliminate Them?
Revisiting W1 Indications

W1s: What Was Done To Enable Better Detection of Them?
Under the web

Incomplete fusion to steel backing
AWS D1.1-94

Structural Welding Code--Steel
4.14 Procedures for Gas Metal Arc and Flux Cored Arc Welding with Single Electrode

4.14.1.5 Flux Cored Arc Welding

The thickness of the weld layers in groove welds, except root and surface layers, shall not exceed 1/4 in (6 mm).
AWS D1.1-96

Structural Welding Code--Steel
Table 3.7
Prequalified WPS Requirements

<table>
<thead>
<tr>
<th>Variable</th>
<th>Position</th>
<th>Weld Type</th>
<th>SMAW</th>
<th>SAW&lt;sup&gt;d&lt;/sup&gt;</th>
<th>GMAW/FCAW&lt;sup&gt;g&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td></td>
<td></td>
<td>3/8 in [10 mm]</td>
<td>Unlimited</td>
<td>3/8 in [10 mm]</td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
<td>5/16 in [8 mm]</td>
<td></td>
<td>5/16 in [8 mm]</td>
</tr>
<tr>
<td>Vertical</td>
<td></td>
<td>All</td>
<td>1/2 in [12 mm]</td>
<td></td>
<td>1/2 in [12 mm]</td>
</tr>
<tr>
<td>Overhead</td>
<td></td>
<td></td>
<td>5/16 in [8 mm]</td>
<td></td>
<td>5/16 in [8 mm]</td>
</tr>
</tbody>
</table>

In 2006, for prequalified WPSs, the maximum root pass thickness is now 3/8 in [10 mm].
FEMA 353

Recommended Specification and Quality Assurance Guidelines for Steel Moment-Frame Construction for Seismic Applications

July 2000
4.1.2 Moment Connection Joints Requiring Removal of Backing Bars

Backing bars shall be removed from the joint when required on the design drawings. Following removal of backing, the root pass shall be backgouged to sound metal, and backwelded.
Would an erector really do that?

Only once!
UT should easily detect this region
Benefits of Backing Removal
Benefits of Backing Removal

• Eliminates notch created by backing
Benefits of Backing Removal

- Eliminates notch created by backing
- Eliminates root discontinuities (cracks, incomplete fusion, slag)
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- Contouring fillet “softens” the 90° intersection
Benefits of Backing Removal

- Eliminates notch created by backing
- Eliminates root discontinuities (cracks, incomplete fusion, slag)
- Contouring fillet “softens” the 90° intersection
- UT inspection results are easier to interpret
4.8 Welding Sequence for Moment Connection of Bottom Beam Flange

When welding the bottom flange of the column flange of welded moment-resisting connections, the following sequence shall be followed:

1. When welding from side A (one side of the beam), the root pass shall begin beyond the center of the joint on Side B, reaching past the beam web (or web plate, for FF connections) through the weld access hold (or opening, for FF connections). After the arc is
AWS D1.8:2009
Seismic Welding Supplement
6.7 Removal of Backing and Weld Root Treatment

When fusible (steel) backing is required to be removed, removal shall be by air carbon arc cutting (CAC-A), plasma arc gouging (PAC-G), grinding, chipping, or thermal cutting. The process shall be controlled to minimize errant gouging. After backing removal (both for steel and nonfusible backing), the weld root shall be backgouged to sound metal. Backgouged joints shall be filled with weld metal as necessary, to achieve at
6.14 Bottom Flange Welding Sequence

Complete joint penetration groove welds of beam bottom flanges to column flanges, or to continuity plates, using weld access holes shall be sequenced as follows:

(1) As far as is practicable, starts and stops shall not be directly under the beam web

(2) Each layer shall be complete across the full width
Revisiting W1 Indications

Changes to the Northridge Record
Changes to the Northridge Record

1994

Problem: W1 incipient cracks

Solutions:
- preheat
- slow cooling
- postheat
- peening
- welding sequence
- process change

2014

Problem: Incomplete fusion

Solutions:
- root pass thickness
- bottom flange welding sequence
- backgouging
Assumption:
UT is effective at detecting weld root problems

New Practice:
Remove backing
Backgouge to sound metal
Apply contouring fillet
UT with backing removed
Changes to the Northridge Record

<table>
<thead>
<tr>
<th>1994</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Problem Description:</strong> Hundreds of damaged buildings</td>
<td><strong>Problem Description:</strong> Widespread original workmanship and inspection issues</td>
</tr>
<tr>
<td>60-80% damaged connections</td>
<td>Concentrated earthquake damage</td>
</tr>
<tr>
<td>2/3rd of inspected buildings were damaged</td>
<td>1/3rd of inspected buildings were damaged</td>
</tr>
</tbody>
</table>
Recommendations

- Use welded steel SMRFs with confidence
- Use AISC Seismic Specs
- Use AISC CPRP Connections
- Avoid special welding-related job requirements except in special situations
Revisiting W1 Indications