Characterization of Submerged Arc Welds from the World Trade Center Towers: As-Deposited Welds and Failures Associated with Impact Damage of the Exterior Columns

Lessons learned from the investigation of building materials, construction, and conditions contributing to the disaster of 9/11 can be used to improve existing and future structures

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ABSTRACT. Intact and aircraft impact-damaged welds from the exterior columns of the World Trade Center towers were evaluated. The fillet welds joining the various steel plates composing the built-up box columns were primarily deposited using submerged arc welding. Characterization of undamaged joints revealed that the welding procedures employed were appropriate relative to contemporaneous standards; no visible surface flaws or subsurface defects were observed. Impact damage of the welds consisted of fracture primarily initiating at and traveling through the heat-affected zone (HAZ) of the steel plates that had rolling planes perpendicular to the travel direction of the aircraft. Failure occurred in this region due to the lower cross-sectional area of the plate and the degraded HAZ mechanical properties (i.e., ductility, toughness with respect to the base plate). Based upon the low-energy, ductile fractures (little plate thinning, slanted fracture surfaces) observed, the failure of the joints absorb only a small fraction of the energy from the impact of the aircraft.

Introduction

A primary goal of the World Trade Center (WTC) investigation conducted by the National Institute of Standards and Technology (NIST) was to explore the building materials and construction and the technical conditions that contributed to the outcome of the disaster (Ref. 1). From an engineering standpoint, it was important to determine why and how WTC 1 (North Tower) and WTC 2 (South Tower) collapsed following the impacts of the aircraft. To apply the lessons learned to existing and future structures. The findings and conclusions of this work are intended to serve as a basis for 1) improvements in public safety through the way buildings are designed, constructed, maintained, and used, and 2) recommended revisions to current codes, standards, and practices regarding these issues. As part of this study, the Metallurgy Division and Materials Reliability Division of NIST analyzed the quality of the steel, weldments, and connections, and assessed the damage and failure modes of the structural steel components. The overview report of the mechanical and metallurgical analysis of the steel (Ref. 2), as well as the complete technical reports covering all other aspects of the investigation, are obtainable on the NIST WTC Web site (http://wtc.nist.gov/).

The high strain rate behavior of exterior column materials, connections, and weldments was required as input for the global impact model that was used to determine the amount of damage associated with aircraft impact. Precollapse images showed that failures of the exterior wall columns in the impact zone resulted from numerous mechanisms: large-scale deformation of the plate material, broken splice connections, cut columns and spandrels, and plate failures near the longitudinal welds (Ref. 3). Each of these damage modes needed to be accurately captured in the modeling efforts (i.e., matching plasticity behavior such as flow stresses and determining appropriate failure strains) to estimate the amount of energy absorbed by the exterior wall. This approximation was critical to calculating the most probable distribution of internal damage within the towers due to the high-density aircraft components.

Constitutive behavior modeling of the first three failure modes (large-scale deformation of the plate material, broken splice connections, cut columns and spandrels) was relatively straightforward, as material testing was available to yield representative data for the mechanical behavior (Ref. 4). However, modeling of the welded joints was more difficult as there was a lack of significant material data available in the literature and inadequate material available, particularly in the heat-affected zone (HAZ), to properly characterize the properties over a wide range of strain rates. Further, while mechanical testing of specimens taken from the welded joints from the columns is possible, it is not straightforward and does not
produce data that accurately describe the properties of the entire weldment. Other data available typically consists of microstructural characterization of the as-deposited welds, with microhardness indentation traverses across the weld geometry, and macro- and microstructural evaluation of failed weldments. Toward this end, the present paper characterized undamaged welds deposited as a part of the fabrication of the exterior columns, and their subsequent failure modes as a result of the aircraft impact. These data were used to gain insights to the high strain rate behavior of the weldments.

Background

Contemporaneous Specifications for Fabrication of the Exterior Panels

From the 9th to 107th floors, the exterior walls of the WTC towers were composed of closely spaced, built-up box columns approximately 14 in. on a side. Fifty-nine of these columns were spaced at 40 in. on center along each face of the building. Adjacent columns were interconnected at each floor level by deep spandrels, typically 52 in. in depth. In general, three full columns were connected to form an exterior column “panel” — Fig. 1. Each panel was typically three stories tall (36 ft) and spanned four floors in the building. This configuration resulted in the individual columns being composed of continuous plates for the flanges (plates perpendicular to the building face) and the outer web (outer plate parallel to face), while the inner face of the column was composed of seven different plates (four pieces of inner web and three spandrels). During construction of the exterior wall, panels were bolted to other panels at column splices and spandrel connections. Further
Table 1 — Identified Exterior Column Panel Pieces from WTC 1 and WTC 2

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Bldg.</th>
<th>Column</th>
<th>Floors</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-13</td>
<td>Part of single column</td>
<td>WTC 2</td>
<td>200</td>
<td>90-92</td>
</tr>
<tr>
<td>C-14</td>
<td>1 column, lower ( \frac{1}{3} ) rd</td>
<td>WTC 2</td>
<td>230</td>
<td>93-96</td>
</tr>
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<td>157</td>
<td>93-96</td>
</tr>
<tr>
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<td>74-77</td>
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<tr>
<td>C-25</td>
<td>1 column, lower ( \frac{2}{3} ) rd</td>
<td>WTC 1</td>
<td>206</td>
<td>89-92</td>
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<tr>
<td>C-40</td>
<td>2 columns, lower ( \frac{2}{3} ) rd</td>
<td>WTC 1</td>
<td>136</td>
<td>98-101</td>
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<tr>
<td>C-46</td>
<td>Nearly full panel</td>
<td>WTC 2</td>
<td>157</td>
<td>68-71</td>
</tr>
<tr>
<td>C-49</td>
<td>Nearly 2 full columns</td>
<td>WTC 2</td>
<td>442</td>
<td>91-94</td>
</tr>
<tr>
<td>C-55</td>
<td>1 column, lower ( \frac{1}{3} ) rd</td>
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<td>209</td>
<td>94-97</td>
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<tr>
<td>C-89</td>
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<td>12-15</td>
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<tr>
<td>C-92</td>
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<td>93-96</td>
</tr>
<tr>
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<td>WTC 1</td>
<td>339</td>
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<tr>
<td>C-99</td>
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<td>70-73</td>
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<td>K-1</td>
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<td>97-100</td>
</tr>
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<td>WTC 1</td>
<td>94-97</td>
<td></td>
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<tr>
<td>M-2</td>
<td>Full panel</td>
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<td>96-99</td>
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<td>M-10a</td>
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<td>82-85</td>
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<td>130</td>
<td>90-93</td>
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<tr>
<td>M-27</td>
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<td>130</td>
<td>93-96</td>
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<td>345</td>
<td>98-101</td>
</tr>
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<td>133</td>
<td>94-97</td>
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<td>N-1</td>
<td>2 full columns</td>
<td>WTC 1</td>
<td>218</td>
<td>82-85</td>
</tr>
<tr>
<td>N-7</td>
<td>Full panel</td>
<td>WTC 1</td>
<td>127</td>
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<td>N-10</td>
<td>2 columns, lower ( \frac{1}{3} ) rd</td>
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<td>115</td>
<td>89-92</td>
</tr>
<tr>
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<td>206</td>
<td>92-95</td>
</tr>
<tr>
<td>N-13</td>
<td>3 columns, lower ( \frac{1}{3} ) rd</td>
<td>WTC 1</td>
<td>130</td>
<td>99-102</td>
</tr>
<tr>
<td>N-99</td>
<td>Nearly full panel</td>
<td>WTC 1</td>
<td>148</td>
<td>99-102</td>
</tr>
<tr>
<td>N-101</td>
<td>Full panel</td>
<td>WTC 1</td>
<td>133</td>
<td>100-103</td>
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</tr>
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<td>Full panel</td>
<td>WTC 1</td>
<td>133</td>
<td>97-100</td>
</tr>
<tr>
<td>S-9</td>
<td>Full panel</td>
<td>WTC 1</td>
<td>133</td>
<td>97-100</td>
</tr>
<tr>
<td>S-10</td>
<td>2 columns, lower ( \frac{2}{3} ) rd</td>
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<td>224</td>
<td>92-95</td>
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<tr>
<td>S-14</td>
<td>Full panel</td>
<td>WTC 2</td>
<td>218</td>
<td>91-94</td>
</tr>
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</table>

Table 2 — Chemical Composition Results of F<sub>y</sub> = 55 ksi Plate from Exterior Columns (in mass fraction x 100). Shown are the Averages with Standard Deviations Given Directly Below.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Plate (in.)</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
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<th>B</th>
<th>N</th>
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<tbody>
<tr>
<td>Flange</td>
<td>0.375</td>
<td>0.17</td>
<td>1.28</td>
<td>0.01</td>
<td>0.01</td>
<td>0.43</td>
<td>0.01</td>
<td>0.02</td>
<td>&lt;0.01</td>
<td>0.04</td>
<td>&lt;0.005</td>
<td>0.046</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>0.031</td>
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<td>Outer</td>
<td>0.25</td>
<td>0.17</td>
<td>1.30</td>
<td>0.02</td>
<td>0.02</td>
<td>0.43</td>
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<td>0.02</td>
<td>&lt;0.01</td>
<td>0.05</td>
<td>&lt;0.005</td>
<td>0.049</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>0.029</td>
<td>&lt;0.005</td>
<td>0.005</td>
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<tr>
<td>web</td>
<td></td>
<td>0.01</td>
<td>0.07</td>
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<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>n/a</td>
<td>n/a</td>
<td>0.004</td>
<td>n/a</td>
<td>n/a</td>
<td>0.004</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Inner</td>
<td>0.25</td>
<td>0.21</td>
<td>1.17</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.07</td>
<td>0.06</td>
<td>&lt;0.01</td>
<td>0.21</td>
<td>0.055</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>0.005</td>
<td>0.008</td>
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<tr>
<td>web</td>
<td></td>
<td>0.02</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
<td>n/a</td>
<td>0.014</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Information regarding construction of the towers can be found in Ref. 2.

**Structural Steels**

The exterior panels were composed of low carbon alloy steels with carbon contents less than 0.002 mass fraction (Refs. 5, 6). Both hot-rolled and quench-and-tempered grades were used. The latter was used for applications where a higher strength to weight ratio was beneficial, such as for the exterior columns on upper floors and corners of the building. Skilling, Helle, Christiansen, & Robertson, structural engineers for the WTC towers, specified the steel to be used for each structural piece by the minimum specified yield strength \( F_y \). For example, a 50-ksi steel is a steel with a minimum yield strength of 50,000 pounds per square inch. The struc-
tural plans called for the exterior columns to be fabricated from 12 grades of steel with $F_y = (36, 42, 45, 46, 50, 55, 60, 65, 70, 75, 80, \text{ and } 100)$ ksi. Two additional grades, 85 and 90 ksi, were initially specified, but later replaced with 100 ksi steel. Each column was composed of one steel grade, but an exterior panel section could contain up to six different grades (one for each of the three columns and three spandrels).

Contemporaneous documents indicate that the flange, outer web, and spandrel plates of the exterior panels were produced by a Japanese steel mill (Nippon Steel), while the inner web plates were primarily supplied domestically (Ref. 5). Though microstructural features of the various plates were similar, chemical analysis confirmed this information (Ref. 6).

**Welding Practices and Specifications**

Pacific Car and Foundry (Seattle, Wash.) constructed a 16 station automated production line to keep up with the schedule of 55,800 tons of exterior panels between November 1967 and August 1970 (an average near 1500 tons per month). At full production, this gantry laid down 2900 lb of weld metal a day (Ref. 7).

The panel fabrication began with forming the inside face using a butt joint to link the spandrel plates to the inner column plates (webs) — Fig. 2A. These were com-

Fig. 3 — A — Precollapse photograph of impact damage to the north face of WTC 1. Location of recovered panels from the impact zone are highlighted: S-9 (pink), M-30 (blue), M-2 (orange), M-27 (green), and N-7 (yellow); B — location of recovered structural elements from the north face of WTC 1.

Fig. 4 — A — Precollapse photograph showing impact damage to panel M-2 (A130: 96-99). B — Photograph of recovered panel showing similar damage patterns. Columns' numbers are indicated in both images.
complete joint penetration welds according to the requirements of AWS D2.0, Specifications for Welded Highway and Railway Bridges (Ref. 7), which probably refers to the 1966 version of AWS D2.0 (Ref. 8). This standard may have been chosen over D1.0 Code for Welding in Building Construction because, at the time, D1.0 was limited to steel strengths under 60 ksi (Ref. 9).

Once the inner face was fabricated, the flanges, butt plates, diaphragm plates, and outer webs were added to complete the panel. After being preheated, the flange and outer web plates were joined by depositing 0.75-in. fillet welds using submerged arc welding (SAW) along the length of the exterior panel (Ref. 7). The fillet weld size was scaled to the web and flange thicknesses, and so was smaller than 0.75 in. for the thinner plates on the upper floors.) Two tandem-arc welds were simultaneously deposited per column, yielding six welds being laid down per pass (three columns per panel). The locations of these welds with respect to the steel plates are shown in Fig. 2B. The panel was then jacked 90 deg, and the other six fillet welds were made along its length. These large fillet welds started 6 in. (150 mm) from the ends of the columns, so manual welding was used to finish the welding of the ends, as well as to make any repairs. Distorted columns were straightened in the conventional manner by heating just after column assembly.

The construction contract states that the submerged arc electrodes used in the WTC towers were purchased to the requirements of ASTM Standard A558 Specification for Bare Mild Steel Electrodes and Fluxes for Submerged-Arc Welding (Ref. 10). This Standard was withdrawn in 1969, and was replaced by an equivalent American Welding Society (AWS) Standard A 5.17 Bare Mild Steel Electrodes and Fluxes for Submerged Arc Welding (Ref. 11). The period from 1965 to 1969 was one of transition, during which AWS assumed the responsibility of maintaining the standards for welding filler materials. Because the contract was awarded in 1967, the fabrication was likely started with the requirements of the 1965 version of the
Fig. 6 — Representative microstructure of a hot rolled, $F_p = 55$-ksi plate from panel M-2. White constituent is ferrite; dark constituent is pearlite (2% nital and 4% picral etch).

Fig. 7 — Cross section of SAW fillet weld between inner web and flange from an undamaged portion of column 129 and panel M-2. A — Schematic showing the location of sample removal; B — metallographically prepared specimen; C — HAZ and weld were determined via optical means (2% nital and 4% picral etch).

ASTM International (ASTM) Standard (ASTM A558-65T, jointly published by AWS as AWS A 5.17-65T), but later exterior column panels may have included some minor changes associated with the conversion to the 1969 version of the AWS Standard (AWS A 5.17-69).

Recovered Exterior Panels from the Impact Zone

As a result of significant volunteer efforts by the Structural Engineers Association of New York (SEAO/NY) and others, 42 exterior wall panels were recovered with construction codes that identified the as-built location in the towers (Ref. 12), Table 1. Of these panels, four from WTC 1 were directly hit by the aircraft and one was located in the impact zone but sustained no related damage (panel N-7) — Fig. 3. No impact-damaged panels were retrieved from WTC 2.

For all “nonimpact” panels, physical damage observed was attributed to events that occurred during or after the collapse of the buildings. Thus, only the four damaged panels in the impact zone were examined to determine the behavior of the welds as a result of the high-strain rate conditions associated with aircraft impact. Further, it should be emphasized that the damage and failure modes noted on these panels were observed after multiple extreme conditions (aircraft impact and the concomitant precollapse fires, the collapse of the buildings and ensuing fires in the rubble, or the subsequent handling related to the recovery efforts). Therefore, the observed damage may be a result of any one or combination of these events. To reduce possible confounding of the data,
portions of the panels with clear precollapse damage, as determined using photographic and video evidence, were used to characterize the behavior of the welded joints.

As an example, the condition of panel M-2 (A130; 96-99) after recovery is remarkably similar to its condition prior to the collapse — Fig. 4A and B. The lower end of this panel was hit directly by the upper portion of the fuselage and the vertical tail stabilizer of the aircraft. Precollapse images show that the columns were bent inward at numerous locations on the panel. A significant bend was directly associated with the concrete slab of the 97th floor level. The floor appears to have acted as a fulcrum over which all three columns and lower portion of the spandrel bent inside the building envelope by several feet. The lower butt plates of columns 129 and 130 (shown in Fig. 4A) were torn off, and the longitudinal welds of the two box columns were split from the butt plate to the first spandrel. The butt plate for column 131 was still intact and the lower portion of the column was relatively undeformed, but also bent inward.

Damage observed on the recovered panel was similar in nature to that observed in the precollapse images. The major bend on the lower portion of the panel remained, though the lower portion of column 131 had been bent back out, presumably during the collapse or subsequent handling of the panel during recovery efforts. Figure 5A and B show the split longitudinal welds on columns 129 and 130. Both flanges from these columns were buckled and the plates were cracked — Fig. 5C. However, the welds found near these bending points remained intact — Fig. 5D.

**Experimental Procedures**

Samples for evaluation were removed from the columns and metallographically prepared using standard techniques. Microstructures were revealed using a combination of two solutions: 1) 4 g of picric acid and 96 mL of ethyl alcohol (4% picral), and 2) 2 mL of nitric acid and 98 mL of ethyl alcohol (2% nital). The ferrite grain size was determined according to ASTM international (ASTM) standard E 1382-97. Grain size measurements were made on longitudinal planes using the Jeffries planimetric method. Results are given in terms of an ASTM grain size number with a measure of relative accuracy, as defined in the standard. The volume fraction of pearlite was determined via an area de-
Results

Base Plate

The three columns from panel M-2 were similar: 55-ksi material with a flange plate thickness of 0.375 in. and webs of 0.25 in. Chemical analyses for the plates are shown in Table 2. Metallographic inspection revealed that all plates were composed of hot-rolled steels. Figure 6A shows a representative micrograph displaying the ferrite-pearlite structure. Banding of the constituents can be noted, though less than in other WTC exterior column plate steels (Ref. 6). ASTM grain size numbers and volume fraction pearlite were equivalent for the three plates (Table 3). The nonmetallic inclusions observed in the plates were typical for hot-rolled steel. The MnS inclusions had a stringer appearance when viewed in longitudinal cross section — Fig. 6B. They were typically thin and, on a qualitative basis, well dispersed throughout the matrix.

Characterization of Intact Submerged Arc Welds

Undamaged welds on all recovered exterior panels listed in Table 1 were visually inspected in the field. Surface flaws such as cracks, undercuts, or overlaps were not ob-
The welds generally conformed to size requirements, and the surface of the adjacent base plates were relatively clean (no spatter). Assessment of the joints for sub-surface flaws was conducted via metallurgical analysis. For this study, \( F = 55 \text{ ksi} \). The welds generally conformed to the strength-plate thickness combinations: those from panel M-2 and from S-9. Samples were removed from areas where the columns were relatively intact. Characterization of only one weld example was shown per joint type below; however, similar welds examined from these six columns yielded like results.

**Weld between Inner Web and Flange**

Figure 7 shows an undamaged weld between an inner web and flange plate from the upper portion of panel M-2, removed approximately 1 m from the upper butt plate of column 129. The weld was made in one pass using a tandem-arc configuration. The HAZ in both plates was determined optically. Examination of all samples on multiple planes along the weld lengths revealed no visible subsurface flaws, i.e., cracks in weld metal, cracks in base plate, incomplete fusion, inadequate penetration, porosity, etc.

A portion of the overall microstructure can be seen in Fig. 8. The weld material was primarily acicular ferrite with coarse carbides dispersed throughout — Fig. 8B. The microstructure of the HAZ, directly adjacent to the weld interface had both blocky and acicular proeutectoid ferrite on the grain boundaries, with a Widmanstätten structure within the prior austenite grain boundaries — Fig. 8C. Bainite may also be present in the structure near high-density carbide regions. Significant grain growth occurred in this area (Fig. 8C) compared to the unaffected plate microstructure — Fig. 6A. The original pearlite in the inner web plate was also tempered near the interface between the HAZ and unaffected base material — Fig. 8D.

Figure 9A shows the approximate location of the hardness trace through the sample. Both the weld metal and the HAZ had higher hardness than the base plate. A spike in hardness was also noted near the weld interface in the HAZ of all samples (Fig. 9B), presumably associated with the morphological changes in the microstructure. While significant grain growth was observed near this location (Fig. 7C), the development of the Widmanstätten structure and other morphologies may have increased the hardness. Similar results were obtained for traces conducted through the other flange and inner web joints.

**Table 3 — ASTM Grain Size Number and Volume Fraction Pearlite for Plates from the Exterior Panels**

<table>
<thead>
<tr>
<th>Plate</th>
<th>Ave ASTM Grain Size #</th>
<th>Relative Accuracy</th>
<th>Ave</th>
<th>St Dev</th>
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<tr>
<td>Flange</td>
<td>12.3</td>
<td>0.5</td>
<td>27.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Outer Web</td>
<td>12.5</td>
<td>0.6</td>
<td>27.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Inner Web</td>
<td>12.1</td>
<td>0.7</td>
<td>29.8</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**Weld between Flange and Outer Web**

Figure 10 shows a joint from panel S-9 (A133: 97–100), located next to panel M-2 — Fig. 3. This sample was removed approximately 1 m from the upper butt plate of column 132. Unlike the weld between the inner web and flange, this weld cross-section revealed a small bead with a larger head over the top. This appearance was likely caused by the tandem-arc arrangement during SAW of the plates, where the fraction of the weld power used here by the leading electrode (depositing the smaller bead) was less than the trailing electrode (depositing the larger bead). The occurrence of the double bead did not significantly alter the appearance of the larger weld microstructure, which was similar to that of the inner web-flange bead — Fig. 8. One difference was that the HAZ under the smaller bead and in the flange plate (Fig. 10C) was smaller than the size of the HAZ in the flange of the inner web-flange joint — Fig. 7C. This appearance may be related to the angle of the electrodes with respect to the joined plates.

Similar hardness traces conducted through the flange-outer web weldment produced results comparable to the flange-inner web traverses (Fig. 9) where both the weld metal and HAZ had a higher hardness than the base plate and a spike in hardness was observed near the weld interface in the HAZ.

**Impact Damaged Welds of Exterior Columns**

Panel M-2 (A130: 96–99) was struck directly by the aircraft. Both precollapse photos and the recovered panel indicated

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**Fig. 11** — A — Location of sample removal for fracture analysis near weld between flange and inner web of column 129 and panel M-2. Plate shown is the flange. Inner web was broken off prior to arrival of NIST. B — Laboratory image showing failure. Fracture (surface indicated by arrows) near weld was a

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**Table 3 — ASTM Grain Size Number and Volume Fraction Pearlite for Plates from the Exterior Panels**
that the lower end butt plates were torn off from the lower portion of columns 129 and 130 (96th floor splice). Nearly the full length of the welds between the flanges and webs in this area fractured in the vicinity of the joints, resulting in the decomposition of the columns into four individual plates. Two typical fractures associated with welds were taken from the lower portion of column 129 approximately 1 m from the lower butt plate.

Weld between Inner Web and Flange

Figure 11A shows the removal location of the sample from column 129. Field observations indicate fracture occurred in the inner web plate near the weld bead. Initial fracture was believed to start near the lower butt plate of the column upon impact (when the butt plate was torn out) and then ran vertically up the column in the inner web. The vertical fracture ended near the lower diaphragm plate of the 97th floor level spandrel. The inner web plate was severed at this location. This portion of the inner web plate was not recovered. The fracture surface of the remaining portion of the inner web was relatively flat with no features readily observable by the naked eye — Fig. 11B.

A corrosion product on the fracture surface, due to prior exposure to weather, was removed via ultrasonic cleaning in a solution of 3 g ethylenediaminetetraacetic acid (EDTA) and 300 mL water. However, the corrosion had consumed the fracture surface to an extent that precluded positive identification of the microscopic fracture mechanism (cleavage facets or dimpling).

Macroscopic examination of the fracture surface in cross section showed that the fracture occurred solely in the inner web plate — Fig. 12. The fracture surface exhibited a few, small steps that were noticeable in cross section — Fig. 12B. With the direction of loading (aircraft impact), it appears that the plate fracture began at the intersection of the web and weld bead, where the cross-sectional area of the joint geometry increased significantly. Microscopic investigation revealed that the fracture initiated at or very near the weld interface and propagated exclusively through the HAZ of the inner web plate — Fig. 13.

Weld between Flange and Outer Web

A fractured joint between the flange and outer web was also taken from column 129 in the same general location — Fig. 14. Similar to the first example, the web plate fractured near the weld bead. Again, it appeared that fracture initiated in the outer web plate near the lower butt plate of the column upon impact and then extended vertically up the column toward the 97th floor level spandrel. The fracture between the outer web and flange stopped short of the lower diaphragm plate of the 97th floor level spandrel. The outer web was still connected to the column, but was pushed inward toward the center of the building.

The weld sample was also cleaned using the 3% EDTA solution. The appearance of the outer web fracture surface was fibrous and/or "woody" when viewed with the naked eye — Fig. 15A. Closer examination using scanning electron microscopy showed that the fracture surface was stepped — Fig. 15B and C. Again, the fracture surface was corroded to the point that no further information could be obtained regarding the microscopic mode of failure.

Macroscopic investigation of the cross-section revealed that fracture occurred solely in the outer web plate; a portion of this plate was still visible after metallographic preparation and etching — Fig. 16B. The fracture surface intersected the outer face of the plate at the toe or root of the weld bead. The cross section of the failed plate showed a jagged, stepped fracture surface with the steps parallel and perpendicular to the rolling plane of the plate — Fig. 16B. These features resulted in a large macroscopic "angle of fracture"
Fig. 13 — Optical micrograph showing fracture of the inner web (arrows) initiating near the weld interface (highlighted in orange) in the HAZ of the plate. Fracture was found to travel exclusively through the HAZ (2% nital and 4% picral etch).

Fig. 14 — A — Location of sample removal for fracture analysis near weld between flange and outer web of column 129 on panel M-2. Plate shown is the flange, with the outer web bent inward; B — laboratory image showing failure. Sample was rotated 90 deg with respect to A. Fracture (indicated by arrows) was a result of airplane impact.

Discussion

Throughout the analysis conducted in this investigation, characterization of the submerged-arc welds used to fabricate the exterior columns suggested that the welding procedures employed were appropriate relative to contemporaneous standards. The welds examined met the required dimensions and contained no visible surface flaws (e.g., cracks, undercuts, or overlaps) or subsurface defects (e.g., cracks in weld metal, porosity, incomplete fusion, inadequate penetration). Further, prior to the extreme loading conditions experienced on September 11, 2001, there were no reported structural problems associated with the welds of the exterior wall panel columns.

through the plate thickness when compared to the fracture that occurred in the inner web (Fig. 12B), which was nearly perpendicular with respect to the rolling plane of the web plate. Microscopic investigation further revealed that fracture of the outer web initiated at the toe of the weld in the HAZ and that the crack propagated exclusively through the HAZ of the web plate — Fig. 17.

The fracture surface of the outer web plate was also evaluated as this portion of the column was still intact. Figure 18A shows the inner face of the web plate bent inward. The mating fracture surface of the outer web to the sample seen in Fig. 16B was also slanted. Measurements taken near longitudinal fractures indicated that very little thinning of the plate occurred — Fig. 18B.
The welds also performed as expected in terms of failure occurring in the heat-affected zone of the base plate material. This failure indicated that the weld metal had sufficient strength and ductility (compared to the base material) during the high-strain rate conditions encountered as a result of the aircraft impact. The significant bend observed on the lower portion of panel M-2 did not produce fracture in the weld metal (Fig. 5D), while tensile forces caused cracking in neighboring flange plates (Fig. 5C). This type of behavior was also observed on columns damaged as a result of the collapse and subsequent handling during recovery.

Two factors caused the location and appearance of the fractures associated with
these weld joints: 1) the direction of the high impact loading with respect to the cross-sectional geometry of fabricated columns composed of welded plates and 2) the diminished HAZ properties of a hot-rolled steel plate with moderately anisotropic mechanical properties.

From the fractures observed, the geometry of the weld, in combination with the direction of aircraft impact, partially dictated where fracture would occur, that being, in the area of lowest cross-sectional area. In both examples, the web plate gauges (0.25 in.) were thinner than both the weld cross-section and flange plates, and thus, fracture occurred through this component. The location of crack initiation, though, as influenced by the joint geometry, occurred at different locations for the two examples shown. For the flange-outer web failure, the crack started at the root of the weld on the outer web (Fig. 17), as this location provided a stress concentrator upon loading. For the flange-inner web case, the initiation site for fracture was the stress concentrator in the area where the flange and web met — Fig. 13. However, the weld geometry employed in manufacturing the exterior box columns was appropriate for the building construction. Sustaining a high velocity impact perpendicular to the weld bead was probably not considered when choosing joint geometry for the application.

The second factor for fracture location was the degraded mechanical properties, with respect to the base metal, of the HAZ. Occurrence of a HAZ is typical for welded low-carbon steels and is not a welding defect. This region was harder due to microstructural changes in the base metal as a result of the heat of welding. Of particular interest is the change in the unmelted base
material directly adjacent to the weld interface. This material would experience the highest temperature excursion (above the 
A_c3 line, the composition-dependent temperature where the transformation of ferrite to austenite is completed upon heating) and faster cooling rate (leading to restricted carbon diffusion) during deposition. These conditions produce metastable phases and morphologies not observed in the unaffected base material. As the hardness of the material increases, a concomitant decrease in the ductility and toughness of the material in the HAZ would also be expected. Both fractures appear to have initiated in these regions near the weld interface — Figs. 13 and 17. The crack then propagated through the regions of lower ductility, generally in the direction of loading, and produced the macroscopic “angle” of fracture that was related to the shape of the heat-affected zone in the respective web plates.

The failure of the joint is not a material-related issue with regard to the fabrication of the web plates. Although the woody or stepped appearance of the fracture surface could indicate failure by classical lamellar tearing of the steel (Refs. 13–16), two factors would dispute this premise. First, the plates with \( F_y = 55 \text{ ksi} \) or greater demonstrated steel making practices shown to reduce the tendency for lamellar tearing (Ref. 6). This fact was supported by the elevated levels of silicon and aluminum that deoxidized the steel to a relatively high degree, with significantly low levels of phosphorous and sulfur (Table 2). This chemical composition control resulted in a low volume fraction of nonmetallic MnS inclusions (on a qualitative basis) that were thin and well dispersed throughout the plate (Ref. 6). Further, the structure (ferrite and pearlite constituents) was not highly banded for the \( F_y = 55 \text{ ksi} \) material (Ref. 6). All of these factors would yield a plate with only moderately anisotropic mechanical properties. Second, no evidence (e.g., cracking that occurred beneath welds in the base metal, usually outside the heat-affected zone, and parallel to the weld fusion boundary) was found in the undamaged weld cross sections to support the conclusion that lamellar tearing was problematic.

The ductile or brittle microscopic mechanism of plate failure could not be determined because corrosion removed the microscopic features on the fracture surface. However, based upon the slanted fracture surface (Figs. 12B and 16B) and the lack of significant web plate thinning (Fig. 18B), these failures were most likely low-energy, ductile failures. The localized ductility of the plate (i.e., small plastic strains in the fracture zone) was related to the high impact loading of the aircraft. As a result, only a small fraction of the total energy absorbed by the exterior wall upon aircraft impact was attributed to the weld fractures. Instead, damage to other structural features (deformation of flange plates, floor system, etc.) played a larger role in the energy absorption.

Summary

Analysis of intact submerged arc welds from the exterior columns of the WTC towers indicated that appropriate welding procedures and joining materials were used during construction. Further, the failure mode of the joints as a result of the aircraft impact was expected. Splitting of the exterior columns into the four individual plates occurred by fracture through the HAZ as this region had a lower cross-sectional area than the weld throat. Additionally, the heat of welding likely degraded the mechanical properties (ductility, hardness) of the material in the HAZ resulting in the crack propagating solely within this feature. Based upon the localized ductility of the fracture and the lack of web plate thinning, failure of the welds absorbed very little of the energy of aircraft impact.

Disclaimer

The policy of NIST is to use the International System of Units (metric units) in all publications. In this document, however, in certain cases, units are presented in the inch-pound system, which was prevalent in the discipline at the time of construction of the towers.

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References


