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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/*).

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KEYWORDS

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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