Journal of Constructional Steel Research 105 (2015) 174–185

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental investigation on the seismic behavior of steel moment connections with decking attachments

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ARTICLE INFO

Article history:
Received 25 June 2014
Accepted 15 November 2014
Available online 15 December 2014

Keywords:
Steel moment resisting frames
Protected zone
Powder actuated fasteners
Puddle welds
Low cycle fatigue fracture
Seismic behavior

ABSTRACT

Steel moment resisting frames rely on large inelastic strains in the beam plastic hinge region to dissipate seismic energy during an earthquake and protect the building against collapse. To limit the potential for premature fracture and because of a lack of test data, fasteners, attachments and defects are prohibited in the plastic hinge region, also referred to as the protected zone in the AISC Seismic Provisions. However, unauthorized attachments and defects occur in many buildings in practice. A set of twelve full-scale moment connection tests were conducted to explore the effect of powder actuated fasteners (PAFs) and puddle welds on the seismic performance of steel moment connections. Both reduced beam section and extended end plate connections were tested with W24 × 62 and W36 × 150 beams. Five specimens included PAFs or puddle welds representing typical steel deck attachment to the top flange of the beam. Three of the specimens included PAFs in a grid over the top and bottom flange and on the web. All twelve specimens passed the qualification criteria for special moment resisting frames (SMRFs) in the AISC Seismic Provisions as they were subjected to a cyclic displacement protocol up to 4% story drift while retaining 80% of their nominal plastic moment capacity. Therefore, the tested moment connection configurations with PAFs and puddle welds were found to produce ductile SMRF type seismic performance. Furthermore, PAFs and puddle welds were found to have negligible effect on cyclic envelope, moment capacity, energy dissipation and strength degradation prior to fracture.

1. Introduction

Special moment resisting frames (SMRFs) depend on large inelastic strains in the beam-to-column connections to dissipate seismic energy and protect buildings from collapse. The ANSI/AISC 341-10 Seismic Provisions for Structural Steel Buildings [2] define the ends of the beams in a SMRF as protected zones at the locations where large inelastic strains are expected. The term "protected" refers to the concept that this portion of the beam should be protected from defects, fasteners, and other discontinuities because their effect on low cycle fatigue fracture is not well understood. For example, AISC 341 [2] prohibits any decking attachments that penetrate the beam flange and any welded, bolted, screwed, or shot-in attachments for other purposes. The extents of the protected zone are defined for each prequalified moment connection included in AISC 358 [3] and are shown graphically in Fig. 1 for two types of SMRF connections.

The concept of the protected zone and related restrictions is largely based on a lack of data. In practice, however, the restriction on fasteners in the protected zone creates issues in construction due to the difficulty in communicating and enforcing the requirements. Many instances of unauthorized attachments are submitted to engineers of record each year, and for each reported case of unauthorized attachment, there are likely many more fasteners and defects in the protected zone that go unreported. However, since moment connection tests in the literature focus on the behavior of the connection itself and thus have well-controlled defect free plastic hinge regions, there is almost no data on cyclic moment connection behavior with defects or fasteners other than welded shear studs. As a result, engineers of record are faced with a difficult decision between leaving the unauthorized attachment, or requiring an invasive repair method without having any data as to the expected seismic behavior associated with either option.

A series of twelve full-scale beam-to-column moment connection tests were conducted to evaluate the effects of powder actuated fasteners (PAFs) and puddle welds applied in the protected zone on the seismic behavior of steel moment connections. The specimens are intended to represent common types of attachments made to the beam in the protected zone such as attachment of steel deck to the beam top flange, attachment of cold-formed steel wall track to the underside of the beam, and attachments for mechanical/electrical nonstructural systems. The objective of the testing program was to investigate whether powder actuated fasteners or puddle welds affected the moment capacity, strength degradation, energy dissipation, and fracture potential of the moment connections as compared to

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http://dx.doi.org/10.1016/j.jcsr.2014.11.006
0143-974X/

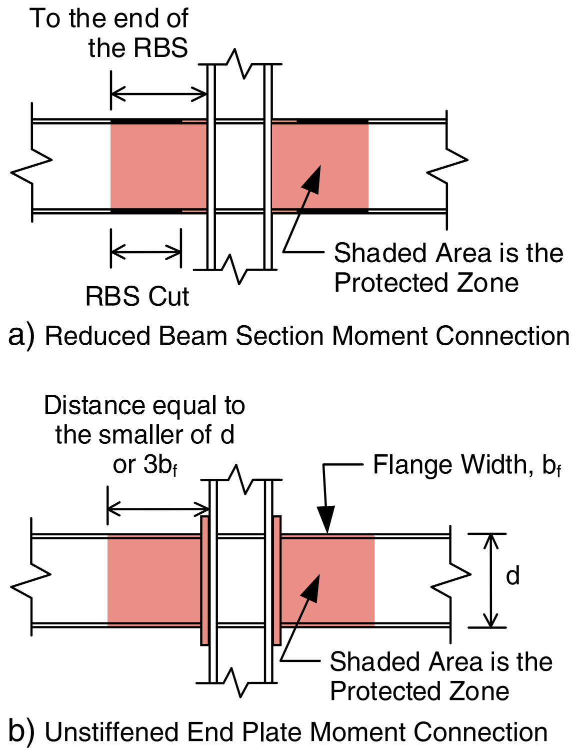

Fig. 1. Examples of protected zone for two moment connection types.

specimens with no fasteners. The special moment resisting frame (SMRF) qualification criteria of AISC 341-10 [2] were used as a benchmark for defining acceptance as the specimens were considered to produce sufficiently ductile behavior if they could retain a significant portion of their moment capacity after being subjected to cyclic loading up to 4% story drift.

2. Background

There have been many experimental programs on full-scale moment connections since the 1994 Northridge Earthquake and the 1995 Kobe Earthquake exposed unexpected fractures in steel beam to column connections. Experimental programs focused on a range of topics including reduced beam section connections (e.g. [6]), extended end plate connections (e.g. [1]), effect of composite slabs (e.g. [9]), panel zone strength (e.g. [11]), and much more. A subset of these testing programs included a composite slab with welded shear studs attached to the beam in the protected zone (e.g. [5,7,9,12,14,18]). Out of this body of tests, one beam-to-column connection specimen with welded shear studs in the protected zone experienced fracture of the flange initiating at the shear stud [14]. It was concluded that the fracture of the beam flange was a direct result of the reduced notch toughness of the base metal caused by shear stud welding. The other specimens in this testing program and specimens from other testing programs did not develop fracture at the welded stud location.

Besides the effect of the fastener itself on stress concentrations and material properties, connections between the concrete slab and the steel beam strongly affect the strain distribution in the beam. Beam-to-column tests using composite slabs and welded shear studs through the protected zone have demonstrated that composite action in the connection region causes significantly increased strain demands in the beam bottom flange [9,12,17]. Both the rapid change from composite section to bare steel beam right at the connection to the column and larger strain demands in the critical bottom flange where the majority of fractures were observed after the Northridge earthquake were considered detrimental.

Fig. 2. Hilti X-ENP powder actuated fastener.

However, the effect of a particular type of fastener on stress concentrations, base metal properties, and degree of composite action is heavily dependent on the type and configuration of fasteners. For this reason, it is necessary to investigate the effect of each type of artifact (i.e. fastener or defect) on moment connection seismic behavior separately.

Powder actuated fasteners (PAFs) are a common method for attaching steel deck to the top flange of steel beams, as well as a common means for attaching nonstructural elements such as cold-formed steel tracks and mechanical, electrical, and plumbing elements to the structure. The fastener (example shown in Fig. 2) is driven into the steel plies using a fastening tool. The effect of PAFs on fracture of steel coupons subjected to monotonic tension has been studied by Beck and Engelhardt [4] and it was determined that coupons with PAFs had higher tensile strength than coupons with equivalent drilled holes. Moreover, a typical coupon specimen with PAF was shown to reach a strain of 17% before fracture which is less than a specimen with no holes, but approximately 70% more ductility than a similar specimen with drilled holes. The increased strength and ductility of steel coupons with PAFs as compared to drilled holes might be attributed to increased strength in the surrounding base metal caused during the fastener application or to residual compressive stresses in the material surrounding the hole. Studies have also been conducted to investigate the high cycle fatigue performance of steel with PAFs (e.g. [13]), tube connections using PAF (e.g. [10]), and steel deck attachment using PAF (e.g. [15]). The extent of material affected by PAF was investigated [20] in which it was found that a particular type of PAF affected the Vickers hardness up to 6 mm from the edge of the fastener. However, the behavior of steel with PAFs subjected to cycles of large inelastic strains, such as those experienced in moment frame plastic hinges, has not been experimentally investigated.

3. Testing program description

3.1. Test setup

The test setup is shown in Figs. 3 and 4. The configuration uses a W14 × 257 vertical column, approximately 3.67 m tall that is restrained against lateral translation at the top and bottom. The W24 × 62 and W36 × 150 beam specimens attach to the column with a bolted end plate connection to allow the same column to be used for every test. Furthermore, the two ends of the beam were used for two different tests to maximize the efficiency of steel used for these tests. Additional details on geometry and reaction frames are given in Toellner [16] and Watkins [19]. Load was applied with an MTS model 201.70 actuator with force capacity of 956 kN in tension and 1468 kN in compression and total stroke equal to 508 mm.

The geometry of the test setup is intended to simulate an exterior column subassemblage of a moment frame undergoing rotation due to