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ScienceDirect
Journal of Constructional Steel Research 64 (2008) 202–213
JOURNAL OF CONSTRUCTIONAL STEEL RESEARCH
www.elsevier.com/locate/jcsr

Experimental and analytical studies on the cyclic behavior of end-plate joints of composite structural elements

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Received 15 November 2006; accepted 10 July 2007

Abstract

The subject of this paper is the analysis of end-plate joints under cyclic and monotonic loading conditions by experimental and analytical studies. The experimental programs are performed on bolted end-plate type joints of composite members under cyclic loading conditions with the purpose to study the seismic response of the considered connection type. The performed experimental research is the second and third steps of an international research project started in 1999 between the Budapest University of Technology and Economics (BME), Hungary and the Technical University of Lisbon (IST), Portugal. The monotonic behavior of the tested joints is followed by the Eurocode standard design method to evaluate the moment resistance and rotational stiffness of the joint. The comparison of the design and the experimental results are performed by the envelope moment–rotation relationships of the hysteretic curves and the design moment–rotation diagram. On the basis of the comparison the modification of the design model is proposed. The monotonic moment–rotation diagram is extended to large rotation regions with the purpose of covering the whole cyclic diagrams until the final failure of the specimen. A semi-empirical method is proposed to approximate the cyclic hysteretic behavior of the studied joints, based on the knowledge of the monotonic moment–rotation curve. This prediction method is based on all the available test results for each behavior mode type (6 tests on steel and 12 tests on composite specimens). The calculated hysteretic curve follows the cycles by polygonal lines taking into consideration the experimental observations. The proposed method establishes the absorbed energy of the consecutive cycles in the case of the studied joint arrangement using standard loading history. The proposed method is applied and verified in the case of each observed failure mode type. By these experimental and analytical investigations the favorable seismic behavior can be derived for the studied joint type.

Keywords: Experimental testing; Bolted joint; Composite member; Modified Eurocode design model; Prediction of cyclic response

1. Introduction

Steel framed structures used in seismic regions can be classified either as non-dissipative structures, for structures where the energy input is sustained by elastic action, or as dissipative structures, where the energy of the earthquake is absorbed by ductile plastic hysteretic behavior. The global ductility in these structures results from the local ductility of the dissipative zones, as shown in Figs. 1(a) and (b) for the case of a moment-resisting frame. The local ductile behavior of these dissipative zones can be quantified by the hysteretic moment–rotation response [1].

From the 1980s extensive research has been performed on the behavior of semi-rigid connections focusing on the monotonic moment–rotation relationship for steel joints [2, 3]. These investigations resulted in new information for various joint configurations, and are reflected in the Eurocode standards. However, in the 1990s, local damage observed in steel structures subjected to large ground motions highlighted the shortcomings of the existing design methods. For this reason international research projects – including experimental, numerical and analytical approaches – have focused on improving our understanding of the behavior of dissipative zones in steel structures [4,5].

From the wide range of ductile joint configurations available, the focus of this paper is on the end-plate type (Figs. 1(b), (c)), which are widely used in seismic resistant frames. Previous studies on the cyclic behavior of end-plate type bolted joints and

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0143-974X/$ - see front matter
doi:10.1016/j.jcsr.2007.07.004

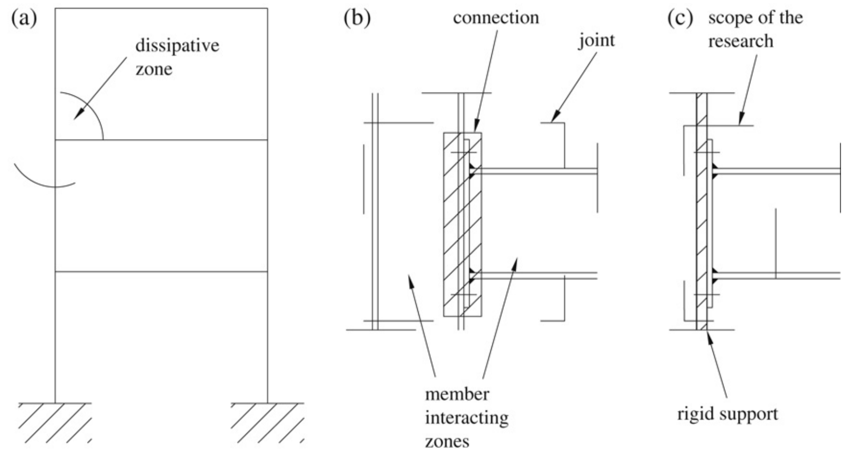

Fig. 1. Definition of the studied joint; (a) Dissipative structure; (b) Joint definition; (c) Studied joint type.

related connection zones have established the possible behavior modes for this connection type. The behavior of such joints is the result of the interaction of several complex phenomena. In order to isolate such phenomena, tests have been performed to analyze the cyclic behavior of both connection components (plates, bolts and welds, for example [6]) and entire joints [7–9].

From the design standpoint, considerable work on connection behavior has been completed in the last two decades [10]. Standard design models have been developed which takes into account the semi-rigidity and partial strength nature of the typical steel beam-to-column joints as reflected by their monotonic behavior. The extension of these design methods to the cyclic case has also been the subject of the considerable research, leading to the development of different levels of mechanical models [11], including component models [12], advanced finite element models [9,13] and semi-empirical phenomenological models [14]. Most, if not all, of the research on end-plate connections has been on steel-to-steel joints. The potential seismic benefits of end-plate joints for composite members have not been studied.

The purpose of the research reported herein is to conduct experimental and analytical studies on the seismic performance of end-plate connections to concrete-filled I-shaped flexural members. The Eurocode design method was first used to determine the monotonic behavior of the studied joints. The results of the tests and analysis were then used to extend this model to the cyclic case, and a semi-empirical method to approximate the cyclic behavior was developed to conduct studies on the optimization of the design of composite end-plate joints.

2. Experimental study

An experimental research program was carried out on 18 end-plate type bolted joints between steel and concrete-filled I-sections and a fixed column stubs to investigate their response under cyclic bending. The test program was carried out as a cooperative effort between the Budapest University of Technology and Economics and the Technical University of Lisbon, where all the tests were conducted. In this systematic test program, the first six specimens (Fig. 3(a)) were used to study basic behavior modes for bolted end-plate type joints between steel I-section members [9]. Following these tests, twelve similar joints of composite beams were tested (Figs. 3(b) and (c)). The details of the experimental programs are presented in [15]. This paper is the continuation of the above referred paper and only a short summary is given about the experimental tests and results.

2.1. Test arrangement, specimens

The test arrangement is basically a cantilever type one, as shown in Fig. 2. The specimens are subjected to cyclic loading, according to the ECCS standard-based loading history [16], in altering directions. In the first test set the specimens are designed with H-shaped steel element (hot-rolled or welded) as illustrated in Fig. 3(a). The composite specimens, with concrete filling and reinforcement or headed studs between the flanges, are shown in Figs. 3(b) and (c).

2.2. Test results

From the observations and the measured force and displacements the cyclic behavior of the specimens – as well as from detailed measurements of the base deformation, bolt elongation, and slips – the cyclic behavior of the connections was evaluated. The cyclic behavior modes of the studied connection are classified by the governing phenomena: the bolt yielding and fracturing in tension (bolt-failure); the plate deforming in bending (plate-failure); the interaction between bolt and plate, and the local plate buckling-failure. The cyclic parameters (ductility, rigidity/resistance degradation, absorbed energy) are also evaluated. Typical hysteretic moment–rotation results are shown in Fig. 4.

The cyclic behavior of the slender, concrete-filled steel sections was studied in detail. The development of the local plate buckling phenomena of the composite members were described and characterized by the moment–rotation relationship and the corresponding cyclic parameters, and compared with the equivalent steel joints (the tests on steel specimens were performed by the author of [9]).