Available online at www.sciencedirect.com
ScienceDirect
Engineering Structures 29 (2007) 1903–1916
ENGINEERING STRUCTURES
www.elsevier.com/locate/engstruct

Testing of semi-rigid steel–concrete composite frames subjected to vertical loads

Jing-Feng Wang[a,*], Guo-Qiang Li[b,c]

[a] School of Civil Engineering, Tsinghua University, Beijing, 10084, People's Republic of China
[b] School of Civil Engineering, Tongji University, Shanghai, 200092, People's Republic of China
[c] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, 200092, People's Republic of China

Received 4 July 2006; received in revised form 12 October 2006; accepted 13 October 2006
Available online 29 November 2006

Abstract

A pair of tests carried out on full-scale semi-rigid composite frames with two stories and two bays are reported. The composite frames undergoing tests are composed of steel columns and steel–concrete composite beams. The beam-to-column connection consists of a flush end plate welded to the beam end and bolted to the column flange. To investigate the influences of semi-rigid connections and composite action of the slab on the performance of the steel frames, the overall response of the frame specimen, the connection behavior, and the beam's behavior when subjected to vertical loads have been measured and analyzed. The nonsymmetrical loading effect is also considered. It is found that the composite endplate connection, which is semi-rigid and of partial strength, has reasonable strength and stiffness, and its rotation capacity satisfies the ductility requirement of no less than 30 mrad for earthquake-resistance. The effects of the flexibility of the connections and the composite action of the slab on the strength, stiffness, and ductility of steel frames must be properly considered in the design.

Keywords: Semi-rigid connection; Composite frame; Composite action; Vertical loads; Testing

1. Introduction

At present, steel–concrete composite construction is extensively used in engineering practice, especially in composite frames for buildings that consist of steel columns and steel–concrete composite beams. This type of composite frame has several structural and constructional advantages, such as high strength and good fire resistance, large stiffness and ductility, the buckling restraints on steel beams provided by concrete slabs, and reduced construction costs and times [1]. These advantages have been recognized and have led to the increasing use of composite frames in some of the recently built tall buildings in China [2].

The strength and stiffness of ordinary steel frames can be significantly improved by a composite of concrete slab with steel beams. This can be achieved by providing a few continuous reinforcing bars across the column lines and ensuring full or partial composite action through the use of sufficient shear studs [3].

In the traditional analysis and design of steel frame structures, the actual behavior of beam-to-column connections is idealized and simplified to two extreme cases: rigid connection and pinned connection. However, as is evident from experimental observations, all beam-to-column connections used in current practice possess some stiffness that falls between the two extreme cases of fully rigid and ideally pinned [4]. Thus, the real connections in steel frames should be treated as 'semi-rigid' connections.

In the past 20 years, a large number of studies have been conducted on bare steel connections and composite connections [4–10]. The behavior of composite connections has been extensively examined, but the majority of this work has concentrated on composite connections between steel columns and composite beams with end-plate connections or flange and web cleat connections. To understand the actual behavior of semi-rigid connections, some researchers started to investigate the effects of semi-rigid connections on the overall behavior of the frame. Moore et al. [11] and Gibbons et al. [12] completed

* Corresponding author. Tel.: +86 10 6277 8987; fax: +86 10 6277 8987.
E-mail address: jfwang@mail.tsinghua.edu.cn (J.-F. Wang).

0141-0296/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2006.10.014

Nomenclature

M	Connection moment
M_{bp}	Design plastic moment resistance of the composite beam in hogging bending
M_u	Ultimate moment capacity of connection
M_{ut}	Test moment at connection
M_{uc}	Predicted moment at connection
$S_{j,\text{ini}}$	Initial connection stiffness
θ_r	Relative rotation of connection
θ_{ut}	Test connection rotation
θ_{uc}	Predicted connection rotation
P	Total test load on a beam
P_u	Total test ultimate load on a beam
L_b	Span of beam
EI_b	Uncracked flexural stiffness for the composite beam
Φ	Beam section curvature
Φ_b	Nominal beam section curvature
ε_{sb}	Average strain on the bottom flange of steel beam
ε_{cb}	Average strain on the top surface of the concrete slab
h_s	Overall depth of the steel beam
h_c	Overall depth of the concrete slab
F_{tr}	Tensile force at the reinforcing steel
F_{bi}	Tensile force at bolt row i
h_w	Height of beam web in compression
t_{wb}	Beam web thickness
t_{fb}	Beam flange thickness
L_r	Distance from the reinforcing steel to the center of the beam bottom flange
L_i	Distance from the bolt bow i to the center of the beam bottom flange
f_{ywb}	Yield strength of beam web
z	Lever arm
K_i	Stiffness coefficient of the component i
E	Young's modulus of steel
D_r	Distance of the upper flange of the beam to the center of the reinforcement
$d_{c,bw}$	Depth of compression in the beam web to be calculated from the equilibrium
d'_c	Distance of the top of the beam from the rebar
d'_b	Distance of the bolts from the rebar
Δ_r	Elongation of the rebar
Δ_s	Slip of the stud at the interface of the slab at the beam top flange
Δ_b	Extension of the bolts

separate tests of two-dimensional and three-dimensional bare steel frames with semi-rigid connections. Leon et al. [13], Jarrett and Grantham [14], Grantham and Jarrett [15], and Dhanalakshmi [16] tested some small composite subframes, whilst Li et al. [3] performed a series of tests on a pair of full-scale composite frames. From the 1990s, some quasi-static tests [17] and fire-resistant tests [18] were performed on isolated semi-rigid steel connections, whilst a few monotonic tests and quasi-static tests were completed on semi-rigid composite connections [19,20] and semi-rigid steel frames [21] in China. However, relatively few tests have been made on full-scale semi-rigid composite frames. Table 1 presents the details of some of these existing composite frame tests.

This paper presents experimental studies on a pair of full-scale semi-rigid composite frames with two storeys and two bays subjected to vertical loads. The main objective is to study the effects of the flexibility of semi-rigid beam-to-column connections and the composite action of slabs on the behavior of composite frames. The nonsymmetrical loading effect is also considered. The findings may be useful for the structural design of semi-rigid composite frames.

2. Experimental program

2.1. Specimens

The test specimens, frame A and frame B, are two-bay full-scale composite frames, as shown in Fig. 1. It can be seen that each specimen is actually a one-and-half storey frame. The steel beams were connected to the flanges of the H-shape columns using flush endplate connections. The span and storey heights of the test specimens are shown in Fig. 2. The section of HW250 × 250 × 9 × 14 is selected for the columns of specimens to keep them elastic during the test. The column foot is designed to be fixed.

In order to restrain the plane frames from lateral movement, frame A and frame B are braced against each other with rebars of 20 mm in diameter.

The steel beams were connected to the column flanges by means of flush end plates of 14 mm in thickness and two rows of M22 Grade 10.9 bolts, as shown in Fig. 3. This is a typical connection in current practice because of its reasonable moment capacity and stiffness. A 140 mm-deep concrete slab was supported by the profile steel sheet decking placed longitudinally with the welded-through stud shear connectors, providing composite action with the steel beam. The width of the concrete slab is taken as 1.5 m, as specified in GB50017 [22].

The slab reinforcement ratio of each specimen is 0.98%. The steel columns are stiffened with transverse stiffeners welded to the web of the columns at the level of the top and bottom beam flange. The reinforcement used is a type of high yield deformed bar. A longitudinal reinforcement of 10 mm diameter is distributed in one layer with equal spacing over the width of the slab beside the column section. Two layers of 6 mm-diameter deformed bars are supplied as a transverse reinforcement to prevent longitudinal splitting failure of the concrete slab (see Fig. 4). They are deliberately cut off at the plane of the beam-to-column connection, in order to prevent the bottom layer of the longitudinal bars from contributing to the moment resistance. The design of the transverse reinforcement and shear connectors for the two specimens are based on BS5950 [23] and GB50017 [22], and a full composite design is assumed.

The trough height and breadth of the metal decking are 76 mm and 344 mm, respectively. The composite beams were