Engineering Structures 172 (2018) 644–662

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Sliding corner gusset connections for improved buckling-restrained braced steel frame seismic performance: Subassemblage tests

Junxian Zhao[a,b,*], Ruobing Chen[b], Zhan Wang[a,b], Yi Pan[c,*]

[a] State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510641, China
[b] School of Civil Engineering and Transportation, South China University of Technology, Guangzhou 510641, China
[c] School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China

ARTICLE INFO

Keywords:
Buckling-restrained brace
Gusset connection
Braced frame
Frame action
Seismic performance

ABSTRACT

Although brace-type hysteretic dampers have been widely adopted to mitigate structural damage under severe earthquakes, their performance was often limited by premature rupture of the welded corner gusset connection or its surrounding framing members due to additional frame action. Such a frame-gusset interaction was found more detrimental for buckling-restrained braced frames (BRBFs). A sliding corner gusset connection, which is connected to beam and column flanges by bolted end plates, but allows sliding deformations at the frame-gusset interfaces via employment of butyl rubber layers, is proposed to minimize such an interaction. Cyclic tests of three steel BRBF subassemblages, two with the proposed sliding configuration and another with the traditional welded one, were conducted to verify effectiveness of the proposed connection. Test results show that significant plastic damages were observed on the welded gusset connection and its surrounding beam. Seismic performance of this specimen was limited by significant out-of-plane and local buckling of the beam prior to brace rupture. Such an undesirable failure could be avoided by the proposed connection, in which the specimen with beam flange reinforcing plates exhibited satisfactory performance up to 4% drift, followed by additional 3% drift with 11 more cycles until brace rupture. The proposed connection is effective in reducing the seismic shear and flexural responses on the framing members, as well as the stress responses at the gusset interfaces. Structural behavior of the two types of gusset connection is compared and future research needs for design of these connections are provided.

1. Introduction

Brace-type hysteretic dampers, such as buckling-restrained braces (BRBs) [1–3], have been widely adopted to mitigate structural damage during strong earthquakes. With the constraining effect of outer restrainer, the inner steel core of a BRB can develop its full yield strength in both tension and compression. In buckling-restrained braced frames (BRBFs), welded corner gusset connections are commonly adopted to connect the BRBs and framing members. In order to develop full hysteresis of the BRBs, these connections should be properly designed to remain essentially elastic under strong earthquakes.

In the past decades, design of such a gusset connection generally followed the uniform force method (UFM) and the generalized uniform force method (GUFM) to obtain both economical and compact bracing connections [4]. These two procedures allow both normal and shear force components being sustained by the gusset-to-beam and gusset-to-column interfaces to transfer the brace action force. However, only brace action force is taken into account in these procedures and additional influence of frame action force is ignored.

As shown in Fig. 1, when a BRBF is deformed under horizontal seismic action, the beam-column joint tends to either open or close. Such behaviors would subject the corner gusset connection to not only brace action but also additional frame action effects. This behaviors were found to impact negatively on the performance of both the beam-column-gusset connection and the framing system [5–16], in which premature fracture was observed at the gusset tips and the surrounding framing members prior to failure of the BRBs. As a result, structural fuse function of the BRBs cannot be successfully achieved as that expected in design.

To address the aforementioned problem, some researchers [6,9,13,14] tried to consider the frame action in design of these connections based on the equivalent strut model [15]. Several design procedures for combining both the brace and frame actions were proposed and validated by frame tests and numerical analysis. However, a

* Corresponding authors at: State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510641, China (J. Zhao) and School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China (Y. Pan).
E-mail addresses: ctjxzhao@scut.edu.cn (J. Zhao), panyi@swjtu.edu.cn (Y. Pan).

https://doi.org/10.1016/j.engstruct.2018.06.031
Received 29 July 2017; Received in revised form 4 June 2018; Accepted 5 June 2018
0141-0296/

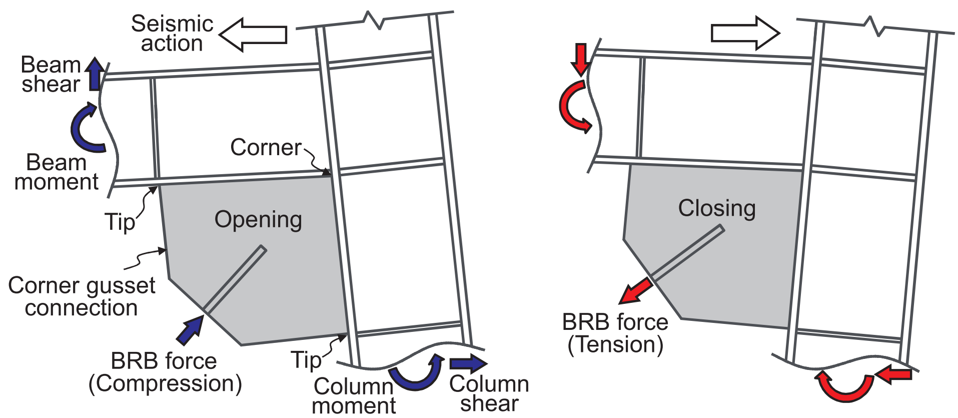

Fig. 1. Opening and closing behavior of steel beam-column joint.

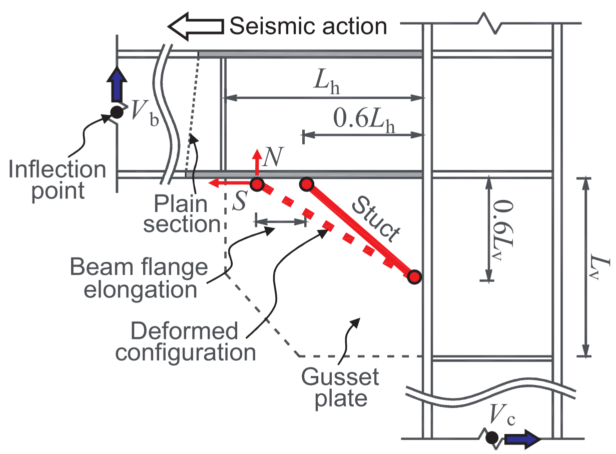

Fig. 2. Equivalent strut model for welded corner gusset connection.

recent study [16] showed that resistance of the gusset connection should be generally improved to sustain the combined action especially when frame action governs. Numerical analysis showed that the equivalent plastic strain demand on the beam plastic hinge rose significantly with the increase of gusset size to sustain the additional frame action, leading to premature failure of the beam member.

Another promising strategy may be the use of alternative gusset configurations to minimize the frame-gusset interaction. Experimental and numerical studies [12,17,18] showed that the use of a rotationally flexible splice placed outside the gusset region is effective to minimize the frame action. However, this configuration cannot be implemented into existing steel frames with full moment connections. Therefore, an unconstrained gusset configuration was proposed by Berman et al. [19], in which full moment connection was adopted while the gusset plate was connected to the beam only and offset from the column. However, the brace action force had to be transferred from the beam end to the column, making the beam end more susceptible to shear yielding [19]. There also existed a large eccentricity between the brace centerline and the centroid of the gusset-to-beam connection, leading to an undesirable gusset size. A recent study [20] verified effectiveness of using double K bracing in RC BRBF, in which the BRBs were connected to the mid-length of columns and beams only to avoid intersection of the brace centerline and beam-column joint. However, sudden loss of one of the BRBs due to buckling or rupture might become detrimental to such a K bracing system.

Based on the aforementioned problems, an innovative corner gusset connection, which is connected to beam and column flanges by bolted end plates, but allows relative sliding at the frame-gusset interfaces via employment of butyl rubber layers, is proposed to minimize the negative frame-gusset interaction. The BRB centerline can be designed to pass through the beam-column joint to ensure minimal influence of brace action force on the performance of framing members. In the following sections, proposal of the new gusset connection is first presented based on the triggering mechanism for frame action force in traditional welded gusset connection. Cyclic test program of three L-shape BRBF steel subassemblages, two with the proposed connections (different details) and another with the traditional welded one, is then presented. Experimental behavior of the frame-gusset-BRB subassemblages, framing members, BRBs and gusset connections are presented and compared among the specimens. The objective of this study are (1) to verify effectiveness and reasonable configurations of the proposed connection in mitigating the frame-gusset interaction, (2) to evaluate influence of different gusset configurations on the structural behavior of gusset connections and framing members, and (3) to gain more insights into the structural behavior of the two types of gusset connection.

2. Proposal of sliding corner gusset connection

2.1. Triggering mechanism for frame action force

Fig. 2 presents the analytical model for estimation of the frame action force on the welded corner gusset connection [13,14]. This model developed from that proposed for the rib-reinforced steel moment connection for analyzing the rib force [15]. An equivalent strut, located at points of 0.6 times the gusset length L_h and height L_v from the column and beam flanges, respectively, was adopted to represent the gusset connection. Axial elongation in the strut, resulting from elongation of the beam bottom flange under bending moment, could be expected if the beam-column joint tends to open. By neglecting the column flange deformations, the shear (S) and normal (N) force components at the beam side gusset interface can be determined from deformation compatibility between the strut and the beam flange. Such a model confirmed the fact that the frame action-induced shear interaction should be the major source for developing the frame action effects. Also note that the shear force component S always shares the same direction with the shear component from brace action [14], which is unfavorable to the structural performance of the gusset connection and should be responsible for premature rupture failure at the gusset interfaces.

2.2. Sliding strategy for mitigating shear interaction at frame-gusset interfaces

Based on the aforementioned mechanism, a sliding gusset connection is proposed to minimize such a frame action effect. As shown in Fig. 3, a gusset plate is welded to two end plates that are sandwiched by several shim plates and the framing members via pre-tensioned high-