Journal of Constructional Steel Research 138 (2017) 432–448

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Shake table assessment of gusset plate connection behaviour in concentrically braced frames

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ARTICLE INFO

Article history:
Received 9 May 2017
Received in revised form 15 July 2017
Accepted 30 July 2017
Available online xxxx

Keywords:
Bracing connections
Gusset-plate behaviour
Standard Linear Clearance methods
Balanced design approach
Concentrically braced frames
Shake table tests

ABSTRACT

Diagonal bracing members and their connections to beams and columns are the key lateral resisting components in concentrically braced frames (CBFs). Although gusset plate connections are widely used to connect bracing and frame members in such systems, their design often involves significant simplifications and idealisations due to the complexity of their behaviour under seismic loading. A conventional approach, which utilises a standard linear clearance zone that permits out-of-plane brace deformation, is typically used in the design of gusset plates. This approach can result in overly large connections with cumbersome details. The desire to achieve an improved balance between the gusset over-strength, on the one hand, and a favourable overall frame performance coupled with practical connection detailing, on the other, has prompted proposals for an improved design approach. However, before new recommendations on the design of gusset plate connections can be provided for use in codified guidance, there is a need to assess the performance of such detailing alternatives under realistic earthquake loading conditions. Accordingly, in this study, the performance of different brace connection configurations and gusset plate designs are examined using shake table testing. The paper describes twelve single-storey full scale shake table tests, which were performed on the AZALEE seismic testing facility at CEA Saclay. In seven of these tests, the gusset plates at the end of the brace members were connected to both beam and column flanges, while in the other five tests these were connected to the beam flange only. Conventional gusset plate design with a standard linear clearance was used for six tests, whereas a more balanced design with a nonlinear elliptical clearance detail was used for the others. The experimental set-up, specimen details, and loading procedures are presented, together with a detailed account of the results and observations. The main findings and their implication on the performance at the local component, as well as the overall frame levels, are highlighted. In particular, it is shown that, provided a number of recommendations are followed, the balanced design approach using a nonlinear clearance can enhance the overall drift capacity, while maintaining control of the failure mode within the bracing member.

1. Introduction

Concentrically braced frames (CBFs) are widely used as lateral resisting systems. They can provide stiff, strong and ductile frames with relatively low cost. Diagonal braces in CBFs are designed to resist large axial forces that are transferred through other frame members, in many cases through the use of gusset plate connections. CBFs are typically designed such that brace yielding in tension and buckling in compression are the main sources for dissipating energy during a severe seismic event [1–4]. The buckling behaviour of the braces depends upon the characteristics of the gusset plate connection, especially its out-of-plane bending stiffness. Traditionally, most of the ductility in CBFs is assumed to be provided by the inelastic behaviour of the bracing members, while that of the gusset plates is disregarded [5].

In Eurocode 8 [6], only the resistance of the tension braces is typically included in the analysis of seismic action effects for conventional diagonal bracing systems. On the other hand, for V-CBFs or inverted V-CBFs both compression and tension diagonals are considered [7]. Because brace compression resistance need not be taken into account for diagonal bracing frames in most cases, European design practice tends to employ bracing members that are more slender than those encountered in other regions where brace compression strength contributes to the design lateral resistance of the CBF. In accordance with capacity design procedures, the diagonal brace members are identified as the dissipative elements of the CBF, and the structural design must ensure

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http://dx.doi.org/10.1016/j.jcsr.2017.07.022

that yielding occurs in these elements before failure occurs in the connections, and before yielding or buckling occurs in the beams and columns [8]. To obtain the required design resistance of these non-dissipative structural components, the design resistance of the brace member is increased by an 'overstrength' factor, and force equilibrium is used to determine a consistent set of forces in beams, columns and connections. Thus, these elements are provided with sufficient resistance to avoid failure. In addition, the detailed design of the CBF must ensure that the expected yielding mechanism occurs, and remains stable within the anticipated range of seismic drift.

As noted above, gusset plates are commonly used to connect diagonal braces to other members of the frame. They are typically aligned in-plane with the frame in a vertical direction. Whether the compression braces buckle in the vertical or horizontal plane is primarily dependent on the orientation of the section shape and the brace end restraints provided by the gusset plate. For out-of-plane brace buckling, member end rotations induce weak axis bending in the gusset plate. At large storey drifts, the end rotation in the post-buckled brace is accommodated by the formation of plastic hinges in the gusset plates [9]. To permit this, a free length is incorporated in the gusset plate perpendicular to the end of the brace and the assumed line of restraint as shown in Fig. 1(a). This gusset design method is known as the Standard Linear Clearance (SLC) model. The recommended size of the free length is typically between $2t_p$ and $4t_p$, where t_p represents the gusset plate thickness.

The SLC method requires that the gusset plate should remain elastic in tension and able to sustain ductile out-of-plane bending in compression, while the connection itself is not considered as a potential dissipative zone. Moreover, all gusset plates should be capacity designed to ensure that the tension and compression resistances of the connection are greater than those of the brace member. Cumulatively, however, these requirements can lead to large gusset plates that are uneconomical and can induce premature damage in other connection elements and frame members [10].

In order to achieve improved and more reliable overall CBF behaviour, previous studies have proposed the introduction of limited tensile yielding in carefully sized and detailed gusset plates using a balanced design approach [11]. Following the conventional capacity design approach, a yielding hierarchy is established in which the strengths of energy-dissipating elements are evaluated and other structural elements are provided with adequate reserve capacities through the use of appropriate overstrength factors. In the case of CBFs, the overstrength tensile resistance of the braces is used to identify the required connection capacity to ensure that the diagonal member yields before the connection. This modular view of CBF design does not directly consider the potentially brittle behaviour of proportionally stronger and stiffer connections under low cycle fatigue conditions. Furthermore, this approach does not differentiate between various connection failure modes which are all required to have the same overstrength resistance. In contrast, the balanced design develops the capacity design approach through the balancing of yield mechanisms in both the brace and the connection. The methodology distinguishes between yielding of an element which implies significant changes in stiffness and inelastic deformation, while maintaining reasonably stable resistance, and failure modes leading to fracture initiation, which imply reduced resistance and inelastic deformation capacity. For the CBFs considered in this paper, the desirable yield mechanism hierarchy can be summarised as:

$$\text{Brace Buckling} < \text{Brace Yielding} < \text{Connection Yielding} < \text{Brace Tearing} \tag{1}$$

When the balanced design method is applied to the design of CBFs, gusset plate yielding is permitted, requiring smaller and thinner gusset plates. In an extensive experimental programme of quasi-static cyclic tests on Special CBFs (SCBFs) designed to US codes, Roeder et al. [12] found that the balanced design method greatly increases the overall deformation capacity. When the balanced design method was implemented with rectangular gusset plates, a 46% increase in drift capacity was obtained. A smaller increase in drift capacity was observed for tapered gusset plates because tapered plates sustain greater damage due to their reduced reserve capacity. While smaller and thinner gusset plates offer potentially a more ductile global CBF response, they are more susceptible to plate buckling in compression, which is an unacceptable failure mode. This is addressed by an alternative detailing proposal [13], which aims at achieving an elliptical yield line configuration in the gusset plate, rather than the conventional SLC detail. This leads to smaller overall gusset plate dimensions, shorter effective lengths and increased plate buckling resistance. This elliptical clearance (EC) offset from the beam and column edges is shown in Fig. 1(b) as N times the plate thickness. Lehman et al. [14] and Roeder et al. [15] observed that specimens with a clear length of $8t_p$ performed well, achieving large drift capacities without weld fracture.

It should be noted that most studies carried out to date have involved simplified quasi-static testing conditions, and there is, therefore, a need to assess the performance under realistic earthquake loading conditions. Although several research investigations have included shake table testing of CBF systems, e.g. [16,17], these have mainly focused on the behaviour of the bracing members and adopted idealised end connection details. In this paper, full scale shake table tests on 12 single storey CBF systems are described. Within these tests, seven frames had the gusset plates connected to the beam and column flanges, while in the other five tests they were connected to the beam flange

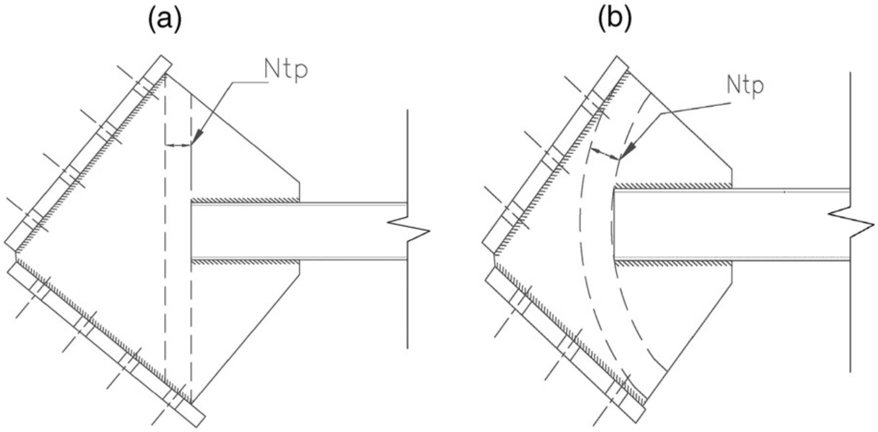

Fig. 1. (a) Standard Linear Clearance design method with clearance length *N* times the plate thickness (t_p) and, (b) Elliptical clearance geometrical layout where the plastic hinge length is *N* times the plate thickness (t_p).