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Shake Table Testing of Concentrically Braced Steel Structures With Realistic Connection Details Subjected to Earthquakes

J. Goggins[a,b,c,*], B.M. Broderick[d], A.Y. Elghazouli[e], S. Salawdeh[a,c], A. Hunt[d], P. Mongabure[g], J. English[f]

[a] College of Engineering & Informatics, National University of Ireland Galway, Ireland
[b] Ryan Institute for Environmental, Marine and Energy Research, National University of Ireland Galway, Ireland
[c] Centre for Marine and Renewable Energy Ireland (MaREI), Galway, Ireland
[d] Dept of Civil, Structural and Environmental Engineering, Trinity College Dublin, Ireland
[e] Imperial College London, UK
[f] Holmes Consulting Group, Christchurch, New Zealand
[g] EMSI, CEA Saclay, France

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ABSTRACT

This paper describes an experimental investigation into the seismic response of concentrically braced steel frames (CBFs). Twelve shake table tests were performed on full-scale single storey frames, each containing a pair of identical brace members. The experimental programme examined the behaviour of brace members with four different square and rectangular hollow cross-sections and a range of gusset plate connection details. The aim of the experimental study was to determine the influence of brace and gusset plate properties on CBF response from serviceability to ultimate limit states, including collapse. Consequently, all test frames were subjected to three levels of seismic excitation: (i) low-level excitation to examine elastic frame response, (ii) medium-level excitation to examine brace buckling and yielding effects, and (iii) high-level excitation to induce brace fracture. A detailed set of data on the seismic response of CBFs with realistic brace members and connections were obtained from the tests. The experiments were conducted under representative dynamic response conditions as opposed to the conventional idealised quasi-static loading procedures employed in previous experimental investigations of CBF behaviour. The results faithfully capture the behaviour of brace-gusset plate test specimens with different non-dimensional brace slenderness, brace cross-section slenderness, connection types and gusset plate detailing. The response variables measured in each test included the shaking table and frame accelerations and displacements, brace elongation and axial force, and brace member and gusset plate strains. The experimental observations include elastic frame vibration properties, acceleration and drift demands, ultimate failure modes and ductility capacity. The brace-gusset plate test specimens remained elastic at low-level excitations, brace buckling and yielding occurred in all medium-level excitation tests, while specimens exhibited brace fracture under high-level excitation. Fracture did not occur in the gusset plate connections irrespective of whether these were designed using a conventional design method with a Standard Linear Clearance (SLC), or a balanced design with an Elliptical Clearance (EC). However, the balanced design approach showed more uniform distribution of plastic strains and led to higher brace ductility capacities when compared to the conventional design method. Based on the test results, available methods for predicting the ductility of bracing members are compared and assessed, and a number of considerations for design are highlighted and discussed.

1. Introduction

Concentrically braced frames (CBFs) offer an economical and efficient form of lateral seismic resistance for structures. For small, more frequent earthquakes, they provide sufficient stiffness and strength to meet serviceability requirements. For larger earthquakes, appropriate seismic design and detailing can ensure a dissipative response and favourable structural performance. Diagonal bracing members in CBFs are critical elements which during strong seismic loading experience repeated cyclic deformations involving yielding in tension and member buckling in compression. The performance of these members depends on various factors, including local slenderness, global slenderness,

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* Corresponding author at: College of Engineering & Informatics, National University of Ireland Galway, Ireland.
E-mail address: Jamie.Goggins@nuigalway.ie (J. Goggins).

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Table 1
Specimen dimensions and properties.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Expt #	Brace-gusset plate specimen ID	Brace cross section dimensions (mm)	Gusset plate thickness (mm)	Brace nominal area (mm^2)	Brace length (mm)	b/t	Non-dimensional slenderness $\bar{\lambda}$	Brace yield strength (MPa)	Gusset plate yield strength (MPa)	Brace plastic resistance (kN)	Gusset plate yield resistance (kN)	Balance factor β_{ww}	Frame natural period (s)
1	S1-CA-G1	80 × 80 × 3.0	12	915	2413	26.67	1.04	373	369	357	1121	0.32	0.216
2	S3-CA-G1	80 × 40 × 3.0	8	674	2427	26.67	2.03	384	337	271	683	0.40	0.235
3	S4-CA-G1	60 × 60 × 3.0	8	674	2425	20.00	1.35	348	337	248	629	0.40	0.225
4	S2-CA-G1	100 × 50 × 3.0	12	854	2413	33.33	1.49	342	369	301	1210	0.25	0.222
5	S1-CA-G2	80 × 80 × 3.0	5	915	2502	26.67	1.03	338	336	322	425	0.76	0.219
6	S2-CA-G2	100 × 50 × 3.0	4	854	2509	33.33	1.55	342	388	302	424	0.71	0.225
7	S3-CA-G2	80 × 40 × 3.0	4	674	2504	26.67	2.05	371	388	265	393	0.67	0.246
8	S1-CB-G1	80 × 80 × 3.0	12	915	2395	26.67	0.98	337	369	321	1121	0.29	0.226
9	S2-CB-G1	100 × 50 × 3.0	12	854	2395	33.33	1.48	340	369	300	1210	0.25	0.258
10	S4-CB-G2	60 × 60 × 3.0	4	674	2437	20.00	1.36	348	388	248	362	0.69	0.242
11	S2-CB-G2	100 × 50 × 3.0	4	854	2433	33.33	1.50	342	388	301	424	0.71	0.220
12	S3-CB-G2	80 × 40 × 3.0	4	674	2420	26.67	1.99	371	388	265	393	0.67	0.246

material yield strength, section shape and end restraint [1]. Tubular sections have been employed successfully in CBF steel structures in seismically active areas around the world. During past large earthquakes, some damage has occurred in connections of CBFs, but typically not in the tubular brace member itself. For example, in the Christchurch earthquakes of 2010 and 2011, only one building with a CBF structure employing tubular members was observed to have any significant damage and this was attributed to poor detailing [2]. Improved design and detailing of tubular brace members and gusset plate connections for CBFs has been proposed (see, for example, [3–8]). However, according to the Tall Building Initiative (TBI) Guideline's in the USA, the use of buckling braces is discouraged for tall buildings in seismically active regions in the USA due to their potential for rapid strength degradation once the brace buckles, which can lead to excessive story drifts due to localisation of damage [9]. However, the TBI group do point out that if they are used, a model should be constructed to represent post-buckling deterioration, ductile tearing due to localised strain reversal during post-buckling cyclic loading and fracture at connections.

As accurate modelling of this complex seismic response presents several technical challenges [1], many experimental studies have been carried out to assess the cyclic inelastic behaviour of bracing members. Early studies examined the hysteretic load-displacement response which was shown to be most strongly influenced by global slenderness [10]. Slender members lost compressive resistance more rapidly than stocky members, resulting in fewer inelastic response cycles and less energy dissipation. Subsequent research examined the factors influencing the fracture life of bracing members. Through experimental testing, both global and local slenderness were found to influence fracture life [11], and empirical expressions for the fracture life and ductility capacity of hollow section bracing members have been proposed [11–14]. Full scale shake table tests were carried out by Elghazouli et al. [15] in the Laboratory for Earthquake Engineering of the National Technical University of Athens (NTUA) to study to behaviour of CBFs. These shake table tests were idealisations of CBFs focusing on the influence of brace slenderness in which the key influence of the brace-beam-column connection was not included in the test specimens [3], and ultimate brace fracture was not observed in most tests.

Gusset-plate connections employed in CBFs in which out-of-plane brace buckling is envisaged must be designed to accommodate the large brace end-rotations experienced at significant storey drifts. This implies the formation of a stable ductile plastic hinge within the gusset plate. The design details must also prevent gusset plate buckling in compression or yielding in tension [16]. However, current design guidance and practice can lead to the use of over-sized gusset plates which reduce the seismic performance of the bracing members themselves. More recently, balanced gusset plate detailing rules have been recommended which result in more efficient connection designs, while improving the overall seismic performance of the CBF [17].

The experimental study described in this paper was designed to investigate the combined influence of brace member dimensions and gusset plate detailing on seismic performance under realistic dynamic response conditions. Twelve experiments evaluated the performance of CBFs at different levels of seismic excitation, including ultimate behaviour, through shake table testing of representative frames incorporating a pair of brace-gusset plate specimens. The main objectives of the shake table tests were to: (i) obtain essential experimental evidence of the ultimate dynamic response of CBFs to realistic earthquake loading; (ii) validate semi-empirical models for ductility capacity during low cycle fatigue failure of hollow section brace members [11,12]; (iii) obtain test data that can be used to investigate the behaviour of practical gusset-plate bracing connections, including the validation of the recently proposed balanced design method and detailing rules [6]; (iv) provide experimental data for the validation of numerical models of CBFs and hollow tubular brace members with gusset plate connections, and for the development of a displacement-based design methodology for CBFs [7].

The experimental arrangements and specimen details are first described, together with an account of the experimental results and observations. Based on the test results, the influence of gusset plate details on the response is outlined, and available approaches for predicting the ductility of bracing members are compared and assessed alongside other key considerations for assessment and design.

2. Experimental set-up

2.1. Brace-gusset plate test specimens

To address the objectives listed above, three different test parameters were varied between experiments: brace cross-section size; brace connection configuration and gusset plate design. These were selected to cover the range of global and local member slenderness found in European design practice, and to assess the effect of conventional and novel gusset plate designs. The following notation is used to identify the properties of the brace-gusset plate specimens examined in individual experiments (Table 1):

- Brace cross-section size:
  - ○ S1 80 × 80 × 3.0 SHS,
  - ○ S2 100 × 50 × 3.0 RHS,
  - ○ S3 80 × 40 × 3.0 RHS,