Journal of Constructional Steel Research 131 (2017) 51–67

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental and numerical assessment of mixed RC beam and steel column systems

M.I. Moharram, D.V. Bompa, A.Y. Elghazouli *

Department of Civil and Environmental Engineering, Imperial College London, UK

ARTICLE INFO

Article history:
Received 2 August 2016
Received in revised form 16 December 2016
Accepted 19 December 2016
Available online 5 January 2017

Keywords:
Hybrid steel/concrete
Experimental assessment
Finite element analysis
Failure conditions

ABSTRACT

This study describes experimental and numerical investigations into the inelastic behaviour of structural assemblages consisting of reinforced concrete (RC) beams connected to steel columns by means of fully embedded shear-keys. A detailed account of the experimental results and observations from a series of fourteen full-scale hybrid steel/RC specimens is presented. In order to provide further insights into the key response characteristics, particularly those related to ultimate failure conditions, a number of numerical sensitivity assessments are also carried out. The numerical studies are undertaken using nonlinear finite element procedures which are validated against previous tests on RC members as well as the experimental results from the hybrid tests presented in this paper. The ability of the numerical models to provide faithful prediction of both RC and hybrid test results, in terms of stiffness, strength and failure mode, using a consistent set of material modelling parameters, provides confidence in the reliability of the simulation techniques. Possible failure conditions for mixed RC/steel members are assessed using a suggested hybrid Mode Index (MI). Based on the experimental and numerical evaluations, simplified analytical representations of the failure surfaces, corresponding to the ultimate modes of behaviour for the hybrid configurations examined in this study, are proposed and discussed.

1. Introduction

The mixed use of structural steel and reinforced concrete (RC) in order to achieve structural and constructional benefits has developed over many years. Early applications have been related to assessing the strength enhancement in encased composite columns traditionally used for fire protection [1,2]. More recent studies on composite columns have focused on examining detailed force transfer mechanisms and on evaluating ductility and failure criteria [3,4]. Other applications of mixed structural steel and RC also include investigations on composite coupling beams as well as their connections to RC walls [5–7], and it was shown that considerable improvements can be achieved through the concrete encasement of steel elements.

Hybrid steel column-to-RC flat slab configurations which use a partially-embedded structural steel profiles were also examined by Eder et al. [8]. In this system, to avoid undesirable punching shear behaviour under seismic loading, the introduction of a gap around the column ensured ductile yielding of the steel shear-key. Other investigations on hybrid members consisting of RC flat slabs, with and without shear reinforcement, connected to steel columns by means of fully-integrated shear heads [9–11], showed improved punching shear strengths in comparison with conventional RC flat slabs. These studies also enabled the development of analytical models [11] that depict the rotational response, flexural strength and punching shear strength as a function of the shear-head embedment length, layout and section size.

Many previous studies have examined the performance of connections between steel beams and RC or composite columns in which the efficiency of various joint configurations was investigated [12–15]. Face bearing plates introduced at the column face and aligned along the depth of the steel beam resulted in significant improvement to the joint shear capacity due to enhancements in force transfer through compression struts between the beam flanges. Detailed assessment of force transfer mechanisms and ultimate failure conditions in systems combining RC or composite beams with steel columns have, in contrast, received comparatively less attention. In preliminary numerical studies by the authors [16], typical shear failure mechanisms involving diagonal tension or shear crushing that can occur in hybrid beams, were explored. More recently, an initial experimental study focusing on the influence of various shear transfer mechanisms was also carried out [17], and enabled the development of a reliable modified shear design approach. Other tests [18,19] on hybrid systems in which fully encased composite columns are connected to RC beams showed that the plastic hinges in the RC beam form away from the beam-column interface and protect the joint zone from significant damage, and that flexural failure governed the ultimate behaviour.

Situations in which RC floor elements need to be combined with structural steel columns often arise in multi-storey buildings, either due to loading and performance constraints or as a result of practical and constructional considerations. However, the design of such 'hybrid

---

* Corresponding author.
E-mail address: a.elghazouli@imperial.ac.uk (A.Y. Elghazouli).

http://dx.doi.org/10.1016/j.jcsr.2016.12.019
0143-974X/

reinforced concrete/steel members' often poses various uncertainties related to the direct applicability of codified rules which are typically developed and validated for conventional RC or structural steel configurations. Such configurations are not conventional RC members and cannot follow the design philosophy stipulated in RC codes such as Eurocode 2 [20]. They are also not classified as fully composite members where design rules and safety checks such as those in Eurocode 4 [21] apply. Therefore, the current study examines the behaviour of hybrid structural configurations in which loads are transferred from RC beams to steel columns by means of fully embedded structural steel shear-keys. The study is part of a wider research project which focuses on complementing existing design guidelines by investigating the structural behaviour and key merits realised from steel profiles embedded in RC configurations [11,17]. The presence of embedded steel shear-keys in RC members creates discontinuities within several regions: hybrid domain (structural steel and RC), non-hybrid domain (RC), and a third transition zone linking the two. This necessitates modifications to typical behaviour of RC members and the need for assessing the governing ultimate criteria.

In this paper, detailed results and observations from an experimental program on fourteen full-scale hybrid systems consisting of RC beams connected to steel columns, using embedded shear-keys, are reported. Complementary numerical studies are also undertaken using nonlinear finite element procedures which are validated against previous tests on reinforced concrete members [22], as well as the experimental results from the hybrid tests presented in this investigation. A number of numerical sensitivity studies are then undertaken in order to provide further insights into the key response characteristics, particularly those related to ultimate failure conditions. Based on the detailed experimental results (crack patterns, surface strain recordings and profile deformations), coupled with the findings from the numerical assessments, simplified analytical representations of the failure surfaces, corresponding to the ultimate modes of behaviour for the hybrid configurations examined in this study, are suggested and discussed.

2. Experimental program

The hybrid structural configurations investigated in this study consist of structural steel columns to which RC beams are connected by means of fully-embedded structural shear-keys. Fourteen large-scale specimens were tested in order to examine the influence of the embedment length of the shear-key l_v, flexural reinforcement ratio ρ_l, presence of transverse reinforcement ρ_w, and the cross-sectional ratio $\eta = (E_c I_c)/(E_v I_v)$. The latter ratio is dependent on the elastic concrete modulus E_c, the elastic moment of inertia of the concrete cross-section I_c, the elastic steel modulus E_v and the moment of inertia of the shear-key I_v. The parameters investigated, as depicted in Table 1, cover a wide range used in design practice and enable adequate assessment of their influence on the structural behaviour of hybrid members.

2.1. Testing arrangement and specimen details

The test setup was designed to simulate loading conditions characteristic of the beam-to-column region of a framed structure in which two partial cantilever beams are connected to the steel column. The same testing arrangement was used in a previous study covering five initial tests from this program [17]. A schematic outline of the rig is given in Fig. 1a, whilst Fig. 1b provides a general view of the test setup. A 1000 kN actuator was used to apply loading in the upwards vertical direction through the column in displacement control, simulating a three point bending arrangement. The reaction to the applied displacement was provided by two secondary frames situated at even distances from the centre of the specimen. The reaction force was transferred to the frame by means of two steel rollers of 100 mm diameter. Plates of 20 mm thickness and 180 mm width were placed between the specimen and steel rollers to avoid local crushing of the concrete at the reaction regions. Displacements were recorded at 12 locations throughout the length of the specimen by means of displacement transducers. In each specimen, 16 strain gauges were typically placed on the longitudinal reinforcement, transverse reinforcement and shear-keys. Crack development and kinematics were captured by means of 'Demec' mechanical dial gauges. Additionally, several of the specimens were instrumented using an advanced Digital Image Correlation (DIC) system to obtain a more detailed and independent verification of the local measurements.

The hybrid members represent the beam-to-column connection region of a typical framed structure with a moment span of about 6 m in which RC beams are connected to steel columns by means of shear-keys. As illustrated in Fig. 2a, the total measured length of the specimens was 3750 mm, whereas the distance between the supports varied between 2300 and 2600 mm. Various configurations were tested in which the embedment length to section depth ratio l_v/h_v varied between 1.0 and 3.6, the stiffness ratio η varied between 4 and 16, the flexural reinforcement ratio ρ_l varied between 0.30 and 1.14%, and the concrete section width-to-depth ratio b/h varied from 0.80 to 1.21. The rebar sizes d_{bl} of Grade S500B ranged from 12 mm to a maximum of 25 mm for the top tensile reinforcement, whereas $d_{bl} = 12$ mm bottom reinforcement bars were provided in all the specimens. Two-legged vertical stirrups of $d_{bw} = 8$ mm diameter at $s_w = 150$ mm spacing were provided in the moment span region in all members. To avoid possible local effects in the vicinity of the reaction plate, a denser stirrup arrangement ($s_w = 70$ mm) was maintained outside the moment span region.

Table 1
Specimen details.

Specimen	Shear-key	RC cross section	l_v (mm)	l_s (mm)	d (mm)	ρ_l (%)	ρ_w (%)	f_c (MPa)3	$f_{c,28\ d}$ (MPa)	f_{sp} (MPa)	Age (days)
B25-R10-W0-S8[b]	HEB200	B360 × 455	500	2600	409	1.09	–	28.6	29.1	2.36	39
B10-R10-W20-S8[b]	HEB200	B360 × 455	200	2600	412	1.09	0.19	27.3	29.1	2.36	28
B25-R10-W20-S8[b]	HEB200	B360 × 460	500	2600	410	1.09	0.19	34.3	37.1	2.96	31
B36-R10-W20-S8[b]	HEB200	B360 × 455	720	2600	408	1.09	0.19	29.9	29.1	2.36	35
B25-R12-W20-S16[b]	UC152	B340 × 435	400	2300	391	1.21	0.20	28.7	29.1	2.36	50
B10-R3-W20-S9[c]	HEB200	B360 × 460	200	2600	425	0.30	0.19	43.0	36.3	3.19	48
B10-R3-W20-S9S[a,c]	HEB200	B360 × 460	200	2600	420	0.30	0.19	43.8	36.3	3.19	41
B25-R3-W20-S9S[a,c]	HEB200	B360 × 460	500	2600	415	0.30	0.19	40.4	36.3	3.19	43
B25-R6-W20-S8b[d]	HEB200	B360 × 460	500	2600	415	0.57	0.19	30.3	37.1	2.96	27
B25-R10-W20-S11[b]	HEB180	B350 × 450	450	2450	405	1.14	0.19	36.1	37.1	2.96	66
B25-R10-W20-S11S[a,b]	HEB180	B350 × 450	450	2450	402	1.11	0.19	39.8	36.3	3.19	36
B25-R10-W20-S8S[a,b]	HEB200	B360 × 460	500	2600	415	1.08	0.19	35.9	37.1	2.96	50
B25-R10-W15-S4[b]	HEB220	B460 × 380	550	2600	340	1.03	0.15	37.9		2.85	33
B25-R10-W15-S4S[a,b]	HEB220	B460 × 380	550	2600	340	1.03	0.15	37.0		2.65	46

[a] Specimens provided with intermediate stiffeners.

[b] Specimens provided with 2ϕ20 + 2ϕ25 tension reinforcement and 4ϕ12 at bottom.

[c] Specimens provided with 4ϕ12 tension reinforcement and 2ϕ12 at bottom.

[d] Specimen provided with 2ϕ12 + 2ϕ20 tension reinforcement and 2ϕ12 at bottom.