Journal of Constructional Steel Research 118 (2016) 156–168

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Available rotation capacity of composite beams with high-strength materials under sagging moment

Huiyong Ban [a,b,*], Mark A. Bradford [b], Brian Uy [b], Xinpei Liu [b]

[a] *Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China*
[b] *Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, UNSW Australia, Sydney, NSW 2052, Australia*

ARTICLE INFO

Article history:
Received 21 September 2015
Received in revised form 8 November 2015
Accepted 9 November 2015
Available online 6 December 2015

Keywords:
Composite beams
High-strength materials
Sagging moment
Finite element analysis
Rotation capacity
Empirical equation

ABSTRACT

Using high-strength (HS) materials in steel–concrete composite beams is an efficient approach to reduce the self-weight and to improve the sustainability benefits of such members. Due to a lack of precise knowledge of the ductility of composite beams beyond their first yield as a result of the non-linear response of their constituent materials, a comprehensive investigation is reported herein to quantify the available rotation capacity of composite beams using HS materials when subjected to sagging bending. An advanced three-dimensional finite element model is utilised to calculate the end rotation of single-point-loaded simply-supported composite beams. The model has demonstrated to be adequate and reliable in terms of predicting the flexural strength and load–deflection response by comparisons with numerous experimental results reported elsewhere. As many as 1380 beams with various strengths of steel and concrete as well as a wide range of the degree of shear connection and geometries are modelled, and both solid slabs and composite slabs using profiled steel decking are incorporated. Analyses of this body of data indicate that the depth of the neutral axis is the most essential parameter for determining the available sagging rotation capacity, of which an increased value leads to a lower rotation capacity. The yield strength of the steel also has noticeable effects with higher values resulting in poorer rotation performance. The available rotation capacity is also sensitive to the span-to-depth ratio of the beams. In addition, the effects of varying cross-sectional geometries, different patterns of shear connector distributions as well as of geometric imperfections and residual stresses are clarified, which are shown to be slight and can therefore be ignored. Finally, a non-linear empirical equation is developed to predict the available rotation capacity of composite beams using HS materials, which covers the range of numerical data with satisfactory consistency. The outcomes provide an important basis for evaluating the ductility of composite beams by comparing with the required rotation capacity.

1. Introduction

High-strength (HS) and high-performance (HP) steels having a nominal yield strength greater than 460 MPa are being utilised increasingly in practice [1–3], and they have been the subject of research (*e.g.* [4,5]). The use of these steels leads to a number of benefits in terms of their structural loading capacities, reductions in self-weight, efficient use of resources and sustainable engineering designs. To fully utilise HS steel in steel–concrete composite beams, the use of complementary HS concrete is normally recommended. However, due to their markedly different non-linear material properties beyond first yield (*i.e.* their poorer plastic performance and lower ultimate strain [6,7]) when compared with conventional-strength materials, the plastic deformation and loading capacities of composite beams incorporating HS materials would logically have different features to those with conventional materials. As a result, relevant knowledge that provides an understanding of the structural performance of such members is much needed.

Unfortunately, most of research in the literature regarding HS steel has been focused hitherto on bare steel structures. This research includes investigations of column buckling behaviour [8–16], seismic performance [17–19], flexural members [20–24], residual stress modelling [25–28], as well as on connections [29–31]. With respect to steel–concrete composite structures, despite a number of research contributions on concrete-filled HS steel tubular columns having been undertaken [32–35], there is surprisingly limited research on HS steel–concrete composite beams. Uy and Sloane [36] conducted two composite beam tests incorporating 690 MPa HS steel, and Zhao and Yuan [37] reported an experimental programme including four composite beams using HS steel (with a yield strength of up to 450 MPa) and HS concrete (with a compressive strength up to 76.8 MPa). Both studies were focused on the flexural strength of such members, and provided preliminary

---

* Corresponding author at: Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China.

E-mail address: banhy@tsinghua.edu.cn (H. Ban).

http://dx.doi.org/10.1016/j.jcsr.2015.11.008

suggestions on methods of calculation. Relevant numerical research is also limited, which seems to only include the outcomes archived by Bradford and Pi [38] and Ban and Bradford [39]. The ductility of composite beams using HS steel has not been addressed hitherto in the literature, which is an essential requirement in plastic analysis design, in particular for achieving a redistribution of bending moments and for favourable seismic performance.

Despite comprehensive investigations on the ductility of composite beams having been reported over the past several decades, only beams with conventional mild steel were considered [40–45]. It has been found at the strength limit state that the use of HS steel in composite beams may lead to premature crushing and limited stress development within the concrete slab due to the increased yield strength of the steel [36,39]; and with the combined effects of the reduced plasticity for both the HS steel and concrete, the ductility of steel–concrete composite beams using HS materials differs from that with conventional materials. As a result, previous models and research outcomes in this area which incorporated conventional mild steel may not apply to composite beams using HS materials. For example, the well-known cross-section ductility model developed by Rotter and Ansourian [45] proposes a ductility parameter χ given by

$$\chi = \frac{0.72 f_c b_c \varepsilon_{cu}(h_s + t_c)}{A_s f_y(\varepsilon_{sh} + \varepsilon_{cu})}, \tag{1}$$

where f_c is the compressive strength of concrete, b_c denotes the width of concrete slab, ε_{cu} is the ultimate strain of the concrete, h_s the height of steel section, t_c the thickness of concrete slab, A_s the cross-sectional area of the steel beam, f_y the yield strength of the steel and ε_{sh} represents the strain at the onset of strain hardening of the steel. Fig. 1 shows the ductility parameter normalised by geometrical parameters ($\chi/[b_c(h_s + t_c)/A_s]$) for an extensive range of strengths for the steel (235 MPa to 960 MPa) and the concrete (20 MPa to 100 MPa). The material properties of the steel with varying grades are listed in Table 1, which were determined based on relevant material test results and prescriptions in national standards [6], whilst the ultimate strain ε_{cu} of concrete was calculated by using

$$\varepsilon_{cu} = \min\left\{2.8 + 27 \times [(98 - f_c)/100]^4, 3.5\right\}‰ \tag{2}$$

in accordance with Eurocode 2 (EC2) [7]. From Fig. 1, it can be seen that the peak value of the ductility parameter corresponds to $f_y = 500$ MPa, which is inconsistent with the common knowledge that conventional mild steel with lower strength probably results in higher ductility. This paradox results from the fact that HS steel with a yield strength in excess of 500 MPa has no visible yield plateau, *i.e.* $\varepsilon_{sh} = \varepsilon_y$, as shown in Table 1. For this reason, the ductility parameter given by Eq. (1) is probably not applicable to composite beams using HS steel. Furthermore, this approach can only evaluate the ductility at the level of the cross-section, in which the effects of the shear span of the beam, the mechanical and distribution parameters of its shear connectors, as well as of plate buckling and the like are not reflected.

Table 1
Material properties of steel with various grades.

E_s (GPa)	f_y (MPa)	f_u (MPa)	ε_y (%)	ε_{sh} (%)	ε_u (%)
210	235	370	0.11	2.50	20.0
210	345	470	0.16	2.50	20.0
210	460	550	0.22	2.00	14.0
210	500	610	0.24	0.24	10.0
210	550	670	0.26	0.26	9.0
210	620	710	0.30	0.30	9.0
210	690	770	0.33	0.33	8.0
210	800	840	0.38	0.38	7.0
210	890	940	0.42	0.42	6.0
210	960	980	0.46	0.46	5.5

In response to the limitations of current research, the ductility of composite beams using HS steel and concrete is investigated herein. The limit state criterion for adequate ductility is normally based on the principle that the available rotation capacity is larger than the required one [43]. This work is focused on the available rotation capacity of composite beams subjected to sagging moments, which is as important as that under hogging moments in seismic design. As the ultimate moment capacity of composite beams using HS materials may not even reach the plastic moment capacity produced by Rigid Plastic Analysis (RPA) [36,39], the rotation capacity is defined as the ratio of the ultimate rotation θ_u corresponding to the maximum moment M_u to the yield rotation θ_y [46,47], as illustrated in Fig. 2. A plethora of composite beams are modelled in the current research by using an improved three-dimensional finite element (FE) model, which is validated against a large number of independent experimental results. The effects of various strengths of the steel and concrete, the degree of shear connection, the distribution of shear connectors, cross-sectional geometries, slabs with profiled steel decking, beam span-to-depth ratio and initial imperfections are all incorporated and elucidated in the study. A non-linear empirical equation then is developed for predicting the available rotation capacity of composite beams with HS materials based on the large number of results from the parametric analyses, and new requirements for the slip capacity of ductile shear connectors are suggested.

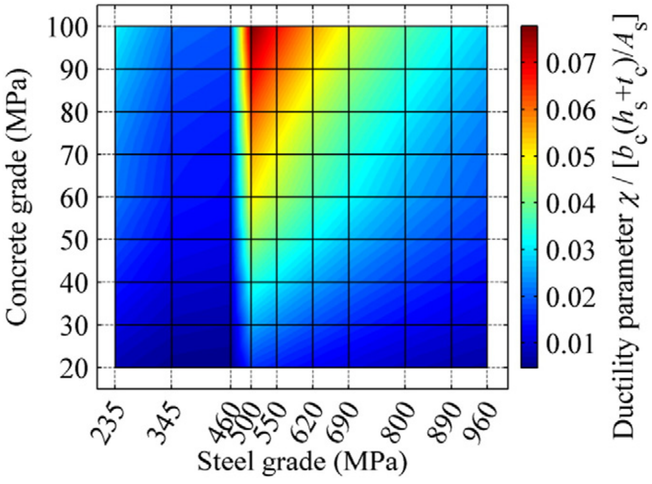

Fig. 1. Normalised ductility parameter for various strengths of steel and concrete.

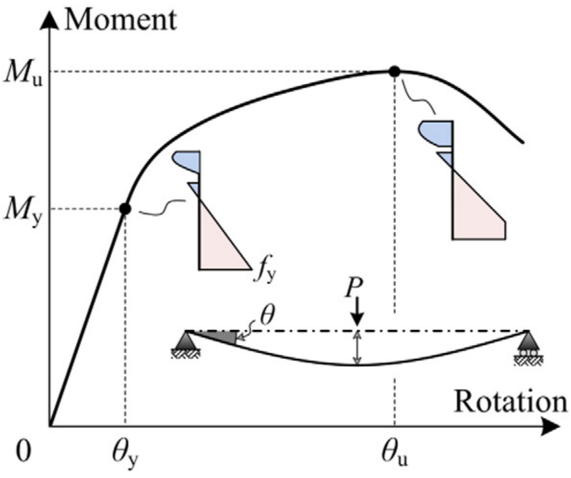

Fig. 2. Definition of rotation capacity.