Journal of Constructional Steel Research 119 (2016) 1–16

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Nonlinear analysis for the pre- and post-yield behaviour of a composite structure with the refined plastic hinge approach

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ARTICLE INFO

Article history:
Received 29 September 2015
Received in revised form 17 November 2015
Accepted 19 November 2015
Available online 17 December 2015

Keywords:
Refined plastic hinge method
Second-order inelastic analysis
One element per member
Higher-order element formulation
Composite structures
High-strength material

ABSTRACT

The computational technique of the full ranges of the second-order inelastic behaviour evaluation of steel–concrete composite structure is not always sought forgivingly, and therefore it hinders the development and application of the performance-based design approach for the composite structure. To this end, this paper addresses the advanced computational technique of the higher-order element with the refined plastic hinges to capture the all-range behaviour of an entire steel–concrete composite structure. Moreover, this paper presents the efficient and economical cross-section analysis to evaluate the element section capacity of the non-uniform and arbitrary composite section subjected to the axial and bending interaction. Based on the same single algorithm, it can accurately and effectively evaluate nearly continuous interaction capacity curve from decompression to pure bending technically, which is the important capacity range but highly nonlinear. Hence, this cross-section analysis provides the simple but unique algorithm for the design approach. In summary, the present nonlinear computational technique can simulate both material and geometric nonlinearities of the composite structure in the accurate, efficient and reliable fashion, including partial shear connection and gradual yielding at pre-yield stage, plasticity and strain-hardening effect due to axial and bending interaction at post-yield stage, loading redistribution, second-order P-δ and P-Δ effect, and also the stiffness and strength deterioration. And because of its reliable and accurate behavioural evaluation, the present technique can be extended for the design of the high-strength composite structure and potentially for the fibre-reinforced concrete structure.

1. Introduction

Steel–concrete composite structure can exploit the higher strength and stiffness from both materials. Therefore, the composite construction are widespread worldwide, in particular the high-rise buildings and long-span structures. Unfortunately, the composite structure is also critical to the intricate behaviour from both materials; specifically the behaviour of the composite member is not simply equal to the summation of both individual steel and concrete section. In fact, the composite structure can behave more likely as the steel or concrete structure, which depends on the material proportion between steel and concrete in the composite section. For example, if the proportion of steel in the composite section is over the rough threshold percentage 0.04%, the member can be regarded as the composite structure. If not, it is regarded as a reinforced concrete structure. More precisely, the cracking behaviour at pre-yield stage which is dependent of the steel proportion of the section should govern the classification between concrete and composite structure. For the sake of investigating the intricate behaviour of a composite structure, a great number of researchers conducted the comprehensive experiments of the composite members, which are divided into two main groups, such as the composite beam and beam-column member. In regard to the composite beam, a large volume of experimental research [1–3] was carried out for more than a few decades, of which the partial shear connection is of much interest. In regard to the composite beam-column experimental research, the nonlinear composite behaviour mainly consists of the buckling of composite column [4,5], confinement effect [6], the local plate buckling of composite column [7], etc.

On the one hand, other scholars studied the composite behaviour by using the numerical approach. For example, there are great amount of numerical approach [8–10], which specifically focus on the partial shear connection of the composite beam at pre-yield stage. They studied this nonlinear behaviour of partially shear-connected slip at the interface comprehensively. However, this slip is not sensitive to the global behaviour of a whole composite structure. From the practical viewpoint, the partially shear-connected interface of a composite beam can be modelled by the effective flexural stiffness approach [11], which can adequately capture the deteriorated flexural stiffness due to the slip at interface at pre-yield range. This approach attracts a number of researchers [12,13], who presented the nonlinear analysis of a composite beam.

The partial shear interaction is less severe and not critical to the composite beam-column member that can be normally ignored. However, the composite beam-column member is vulnerable to the material

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http://dx.doi.org/10.1016/j.jcsr.2015.11.013
0143-974X/

Nomenclature

f_y, f_{ry}	yield stress of the steel section and reinforcement bar, respectively
f_c	ideal compressive yield stress of concrete
I_g	gross second moment of area (uncracked) for those of composite I_f with full shear connection and steel I_s section
M_0, S_0	bending moment and shear force at mid-span, respectively
$\overline{M}_0$, $\overline{S}_0$	equivalent bending moment and shear force at mid-span, respectively
N_f/C_f	degree of partial shear connection
P_c, M_c	axial force capacity and bending moment capacity, respectively
S	plastic section modulus (cracked) for those of composite S_f with full shear connection and steel S_s section
y_c, y_p	centroid (plastic centroid) and plastic neutral axis, respectively
αx	effective depth of the ideal concrete compressive yield stress block
α_n	parameter for the biaxial bending interaction capacity domain
δA	cross section area of a strip of layer
ε_s, ε_c	yield strain of steel material and concrete material, respectively
ε_{su}, ε_{cu}	ultimate strain for ductility of steel and concrete material, respectively
σ, ε, ϕ	normal stress, normal strain and curvature of the fibre, respectively
ϕ_i, ϕ_f, μ	initial and full yield function, and hardening parameter, respectively

yielding due to interaction between axial and bending actions. Therefore, many researchers, such as [14], developed the cross-section analysis to determine the ultimate capacity of the concrete section or steel–concrete composite section in the context of the plastic zone method [15–18]. Unfortunately, the well-known setback of the plastic zone method is inefficient convergence and time-demanding stress numerical integration process.

The counterpart of the plastic zone method is the plastic hinge approach, which simulates the overall material behaviour of the element section at the hinge (i.e. at element node), and further the lump-sum spring stiffness in terms of the load–deformation relationship characterises the material condition of the element section. The plastic hinge approach always ensures the reliable numerical convergence thanks to the load–deformation relationship being consistent and compatible with the conventional finite element method (i.e. stiffness method) as well as eliminating the time-demanding numerical integration process that is used in the plastic zone method. In order to characterise the material condition in alignment with the plastic hinge approach, the cross-section analysis [13,19] is therefore indispensable to evaluate the lump-sum material condition of the non-uniform and arbitrary element section. And, on the basis of this, a few scholars [20–22] presented the numerical nonlinear analysis of a whole composite structure.

In order to strengthen the modelling capacity, promise the efficient solution as well as facilitate the effectiveness in computer modelling, this study presents a second-order inelastic numerical analysis of an entire composite structure in context of the higher-order element with the refined plastic hinge. In regard to the material nonlinearities, the inelastic analysis comprises the cross-section analysis (for the non-uniform and arbitrary composite section under the interaction between axial load and bending), which is extended from the previous work [13], but well align with the refined plastic hinge approach [20] (for gradual yielding, full plasticity and strain-hardening effect due to interaction). In regard to the geometric nonlinearities, the second-order analysis is based on the higher-order element formulation with element load effects (for the P-δ and P-Δ effect, large deformation behaviour, snap-through buckling, pre- and post-buckling), which can provide the accurate first- and second-order element load solutions [23,24].

2. Higher-order displacement-based element with element load effect

The higher-order transverse displacement interpolation function of an element not only fulfils the compatibility condition in Eqs. (2) & (3), but also the force equilibrium equation in Eqs. (7) & (8) in order to derive a higher-order element, as originally proposed by Chan and Zhou [25]. The mid-span moment M_0 and shear force S_0 are respectively introduced into Eqs. (4) & (5) as shown in Fig. 1, which enable to measure additional deflection due to element load effect and the second-order coupling effects [23,24]. Further, the elastic material law follows in the higher-order element function.

$$v(x) = \sum_{i}^{p} c_i x^i \tag{1}$$

in which c_i is unknown coefficient solved from boundary conditions given from Eqs. (2) to (8); p is polynomial of order up to 5 in this sense. In the transverse deflection v in the y direction,

$$v = 0 \quad \text{and} \quad \frac{\partial v}{\partial x} = \theta_{z1} \quad \text{at}\ \zeta = 0 \tag{2}$$

$$v = 0 \quad \text{and} \quad \frac{\partial v}{\partial x} = \theta_{z2} \quad \text{at}\ \zeta = 1, \tag{3}$$

while the equilibrium equation of bending and shear force given by

$$EI_z \frac{\partial^2 v}{\partial x^2} = Pv - M_{z1}(1-\zeta) + M_{z2}\zeta + M_0 \tag{4}$$

$$EI_z \frac{\partial^3 v}{\partial x^3} = P\frac{\partial v}{\partial x} + \frac{M_{z1}+M_{z2}}{L} + S_0 \tag{5}$$

where

$$\zeta = \frac{x}{L}. \tag{6}$$

$$EI_z \frac{\partial^2 v}{\partial x^2} = Pv + \frac{M_{z2}-M_{z1}}{2} + M_0 \quad \text{at}\ \zeta = \S \tag{7}$$

$$EI_z \frac{\partial^3 v}{\partial x^3} = P\frac{\partial v}{\partial x} + \frac{M_{z1}+M_{z2}}{L} + S_0 \quad \text{at}\ \zeta = \S \tag{8}$$