THERMOMECHANCIAL ANALYSIS OF COMPOSITE STRUCTURES USING OPENSEES

Jian Jiang [a], Guo-Qiang Li [a,b]and Asif Usmani [c]

[a] Department of building Engineering, Tongji University, Shanghai, 200092, China
[b] China State Key Laboratury for Disaster Reduction in Civil Enginering, Tongji University, Shanghai 200092, China
[c] School of Engineering, The University of Edinburgh, Edinburgh EH9 3JF, Uk

Abstract
The OpenSees framework has been extended to deal with steel-concrete composite structures under fire conditions. The single section and rigid link methods can be used to model composite beams and slabs in OpenSees. The former models the composite beam by defining a single beam section including steel beam and concrete slab and the latter is to define them separately interconnected by rigid link element. The equivalence of these two methods is verified by mechanical tests and fire tests on simply supported composite beams. Good agreements achieved between OpenSees predictions and experimental measurements shows the robustness of the developed OpenSees.

Keywords: composite structures; OpenSees; thermomechanical analysis.

INTRODUCTION

The fire performance of composite steel and concrete beams can be assessed by conducting standard fire tests (Wainman and Kirby 1988; Newman and Lawson 1991; Zhao and Kruppa 1995). Although the experimental investigation of composite beams in fire gives fundamental understanding of the fire behavior of composite beams, it is impossible to cover all application domains and robust numerical analysis should be used to make up the experimental limitation. A two-dimensional analytical model was proposed by Oven (1996) to consider the partial interaction in composite beams. Huang et al. (1999) developed a separate shear connector element permitting modelling of full, partial and zero interaction between the steel beam and concrete slab. Sanad et al. (2000) modeled the Cardington restrained beam test using a grillage of beam elements to investigate the influence of restrained thermal expansion and thermal bowing on the forces and moments developed in the composite structures in fire. Fakury et al (2005) presented two-dimensional finite element analysis of semi-continuous composite beam with different temperature distribution regimes. Benedetti and Mangoni (2007) extended the method of the Fourier series expansion to the fire analysis of composite beams concerning deformable shear connectors. Ranzi and Bradford (2007) presented an analytical model for structural analysis of composite beams in fire accounting for both longitudinal and transverse interaction by means of the principle of virtual work. Hozjan et al. (2011) presented a strain-based finite element to account for slip between steel beam and slab. Fang et al. (2011) proposed two robustness assessment approaches for steel-framed composite construction under localised fire using a grillage model of beam elements.

These numerical analyses of composite structures at elevated temperature were carried out based on specialist programs such as VULCAN, ADAPTIC, SAFIR, and commercial packages such as ABAQUS, ANSYS and DIANA. Although specialist programs are cost-effective to purchase and easy to use they lack generality and versatility. The commercial packages require substantial recurring investment for purchase and maintenance that often make them unaffordable for researchers and deter new entrants to the field.

OpenSees (McKenna 1997) is an open source object-oriented software framework developed at UC Berekeley and supported by PEER and Nees. OpenSees has so far been focussed on providing an advanced finite-element computational tool for analysing the non-linear response of structural frames subjected to seismic excitations. This paper presents an augmentation of OpenSees to enable two-dimensional thermomechanical analysis of composite beams. This involves creating a new thermal load class, modifying existing material classes to include temperature dependent properties and modifying methods in element and section classes in OpenSees. A composite beam can be modelled in two alternative ways in OpenSees. One is to define a fibred single beam section combining the steel beam and concrete slab. The other model is to define them separately using beam elements interconnected by rigid link element. Four mechanical tests and two fire tests on the composite beams are chosen to verify the performance of the developed OpenSees and the equivalence of the two modeling methods.

1 OPENSEES MODEL

New subclasses were implemented and new methods were developed that derive behavior from existing components in OpenSees. These involved creating a new thermal load pattern class, and modifying existing material classes to include temperature dependent properties. Fig.1 shows the class hierarchy of new classes added in OpenSees using the graphical Unified Modeling Language notation (Booch et al. 1998).

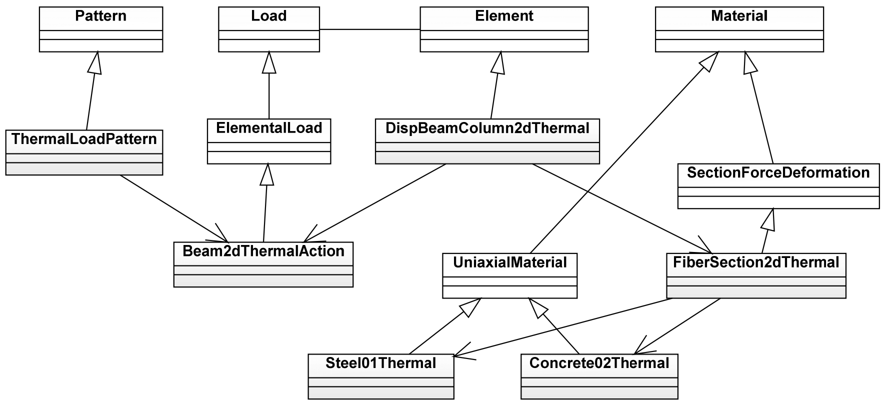


Fig. 1 Class diagram for thermomechanical analysis in OpenSees

A composite beam can be modeled in two alternative ways in OpenSees. One is to use a single section including steel I beam and concrete slab representing the composite beam. The other is to define steel beam and slab separately with rigid link connected between them to model the full shear connection condition. The command “rigidLink” was used to construct a single multi-point constraint between steel beam and slab to model the shear connection relation. Two rigid-link types “bar” and “beam” are offered in OpenSees. The “bar” type only constrains the translational degree-of-freedom and “beam” type constrains both translational and rotational degrees of freedom. In this paper, the “beam” type is used to model the full shear connection between the steel beam and concrete slab. The schematic of these two OpenSees models are shown in Fig. 2.

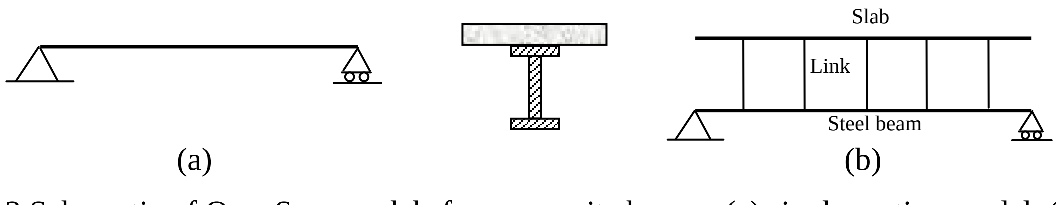


Fig. 2 Schematic of OpenSees models for composite beams: (a) single section model; (b) rigid link model.

2 VALIDATION

In this section, the performance of developed structural analysis of composite beams exposed to fire in OpenSees was verified by comparing with experimental results. These comparisons started from four tests on composite beams under mechanical load only followed by two tests on composite beams exposed to standard fire.

2.1 Composite beams at ambient temperature

Four simply-supported composite beams under mechanical load at ambient temperature were analysed using OpenSees. These tests included one tested beam (B4) from Amadio et al. (2004) and the other three beams (A3, A5, U4) reported by Chapman and Balakrishnan (1964). The beam U4 was subjected to uniformly distributed load and the others subjected to concentrated load. The test set up and beam dimensions are shown in Fig. 3. The existing 2D beam element DispBeamColumn2d was used to model the composite beams in OpenSees. The existing material classes Steel01 and Concrete02 in OpenSees were used to model the steel and concrete material respectively. Fig. 4 shows the comparisons of mid-span deflection from measured and predicted results of OpenSees as well as Oven (1996) and Huang et al. (1999). Good agreement achieved between the single section and rigid link models in OpenSees shows their equivalence to model two-dimensional composite beams under mechanical load. The OpenSees predictions agree well with experiment measurements.

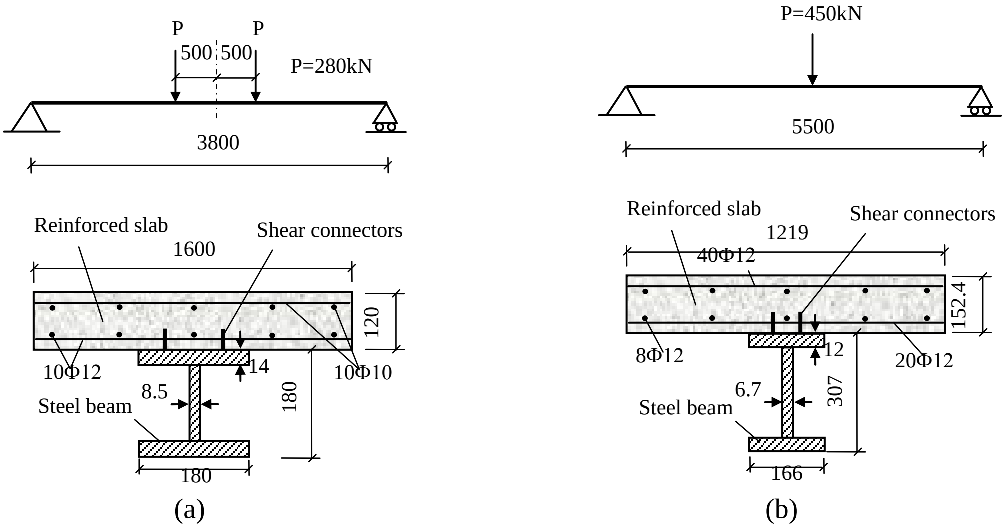
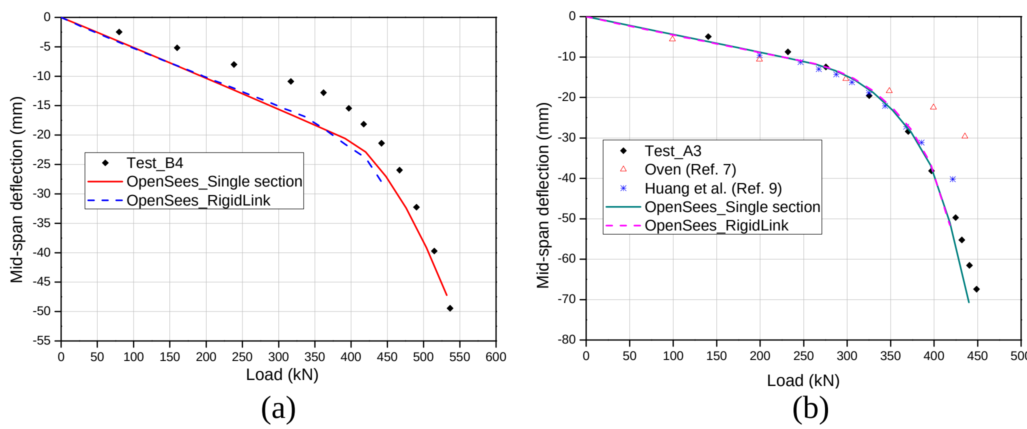
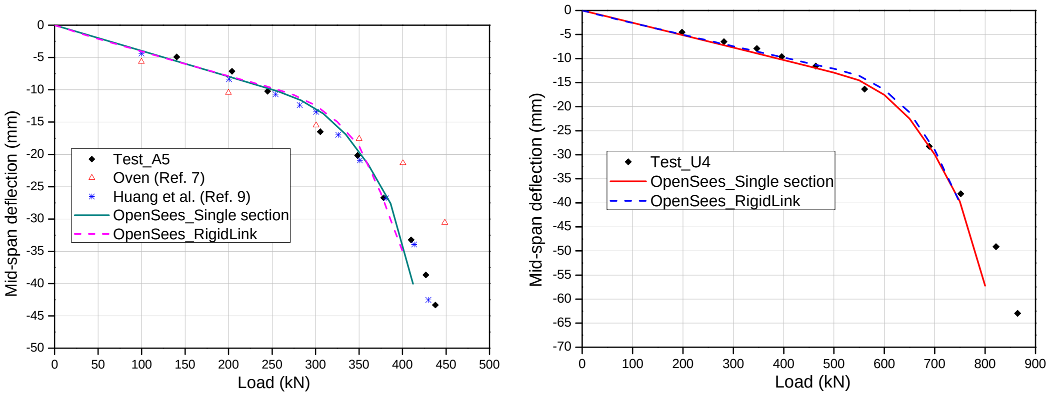


Fig. 3 Schematic of tested beams: (a) composite beam B4; (b) composite beam A3, A5 and U4. (all dimensions in mm)





(c) (d)

Fig. 4 Comparison of measured and predicted mid-span deflection of tested beams: (a) beam B4; (b) beam A3; (c) beam A5; (d) beam U4.

2.2 Composite beams at elevated temperature

Two ISO834 standard fire tests (Test 15 and 16) on simply supported composite beams were conducted by Wainman and Kirby (1988). The structural configuration is shown in Fig. 5. The material class Steel01Thermal and Concrete02Thermal in OpenSees were used to mode the steel and concrete material in the composite beam. Their temperature dependent properties are shown in Fig. 6. The modified beam element DispBeamColumn2dThermal was used to model the composite beams in OpenSees. Fig. 7 shows the temperature distribution in different components of the two tested composite beams. No concrete slab temperature profiles were reported and therefore the temperature distributions through the thickness of the slabs were referred to Eurocode 4 (2005). Fig. 8 shows the comparisons of mid-span deflection from measured and predicted results of OpenSees and Huang et al. (1999). The OpenSees predictions show reasonable agreement with test results. The equivalence between single section and rigid link models in OpenSees is verified again for composite beams under fire conditions.

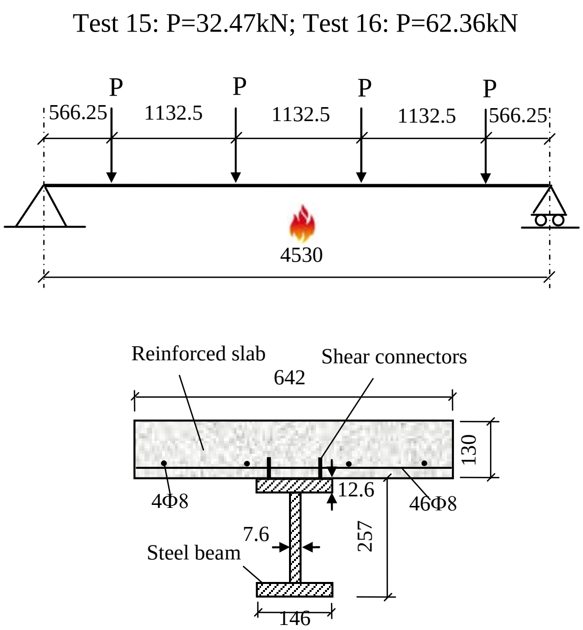
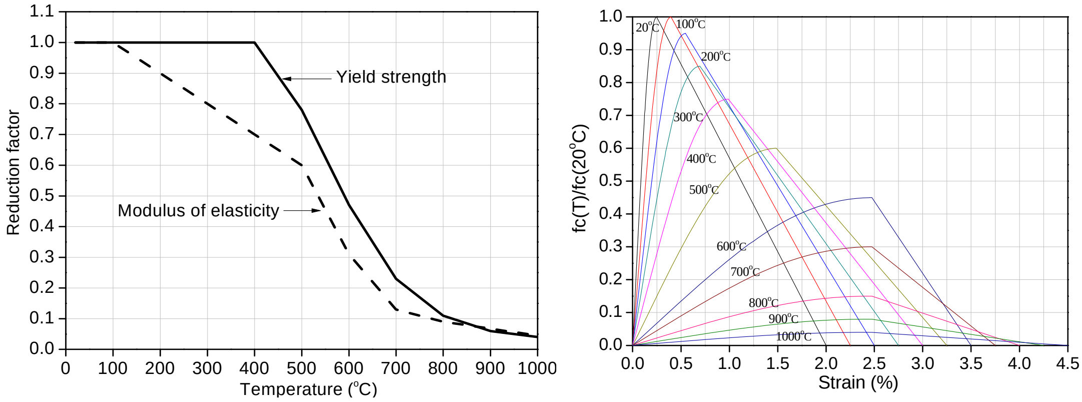


Fig. 5 Schematic of tested composite beam (Test 15 and Test 16) (all dimensions in mm)



(a) (b)

Fig. 6 Material properties at elevated temperature in OpenSees: (a) yield strength and elasticity modulus of steel; (b) compressive stress-strain relation of concrete

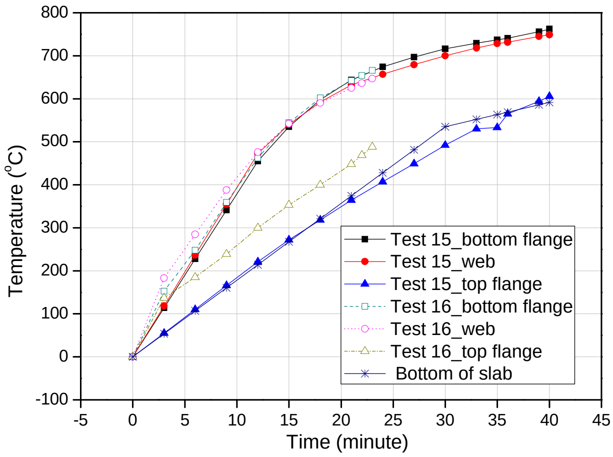
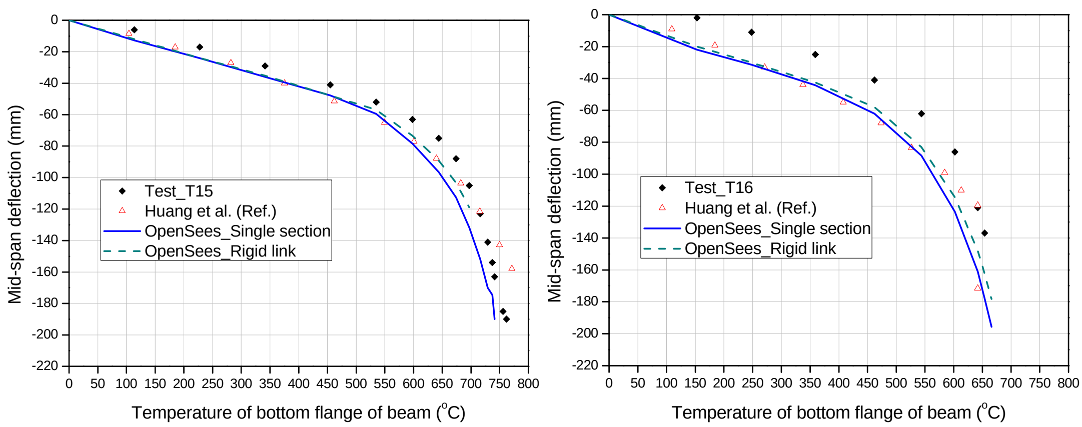


Fig.7 Temperature distribution in the composite beams against time



(a) (b)

Fig. 8 Comparison of measured and predicted mid-span deflection of tested beams: (a) beam Test 15; (b) beam Test 16.

3 CONCLUSIONS

The OpenSees framework has been extended to perform thermomechanical analysis of composite structures. The performance of the developed capacity in OpenSees is verified by predicting mid-span deflection of tested composite beam under mechanical and thermal load respectively. Good agreement is achieved between OpenSees predictions and experimental measurements. The single section and rigid link method is proved equivalent to model the composite beam in OpenSees. The further work will focus on modeling three-dimensional steel-framed composite structures using OpenSees (e.g. Cardington tests).

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