Construction and Building Materials 90 (2015) 18–35

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Damage mechanisms in cementitious coatings on steel members under axial loading

Suwen Chen [a,b,*], Liming Jiang [b,c], Asif Usmani [c], Guo-Qiang Li [a,b], Chu Jin [b]

[a] State Key Laboratory for Disaster Mitigation in Civil Engineering, Shanghai, China
[b] College of Civil Engineering, Tongji University, Shanghai, China
[c] School of Engineering, The University of Edinburgh, Edinburgh, UK

HIGHLIGHTS

- Mechanical properties and bond strengths of cementitious coatings are determined.
- Monotonic axial loading tests on cementitious coated steel members were conducted.
- A cohesive zone finite element (CZFE) scheme for damage modelling is established.
- Damage mechanisms of cementitious coatings on axially loaded steel are revealed.

ARTICLE INFO

Article history:
Received 19 March 2013
Received in revised form 14 February 2015
Accepted 12 April 2015
Available online 16 May 2015

Keywords:
Cementitious fire protection coating
Cohesive zone finite element (CZFE)
Damage mechanism
Axial loading
Monotonic loading test
Steel structure

ABSTRACT

Cementitious coatings have been widely used as fire protection for steel structures, but they are vulnerable to structural deformations or vibrations, which may lead to reduction in their effectiveness and cause severe economic loss in the event of a fire. For buildings in practice, the problem can be critical because the coatings are assumed to be in good condition as they are usually hidden underneath architectural finishes, making it difficult and expensive to carry out routine inspection. To determine the actual fire resistance of a building after a moderate or severe loading event or a relatively long period of service, it is imperative to understand the performance of the coatings and to develop effective damage estimation methodologies. Loading conditions in a real buildings can be complex, however as there is inadequate previous work in this field, it is considered more important at this stage to determine the fundamental damage mechanisms in cementitious coatings on steel members subjected to axial loading, as investigated in this paper through experimental and numerical studies. At first, tests are carried out to obtain mechanical properties of the coating and the bond properties between the coating and the steel substrate. Then, a series of monotonic loading tests are conducted on axially loaded steel members to observe damage propagation in coating specimens. Subsequently, a cohesive zone finite element (CZFE) scheme is presented for modelling the damage with both interfacial and internal damage considered. The effectiveness of the proposed CZFE scheme is validated by comparison with different numerical approaches, interlaminar stress analysis and monotonic loading tests. From monotonic loading tests and CZFE numerical analyses, damage mechanisms in cementitious coatings on axially loaded steel members are clearly revealed. Under tensile loading, the damage begins with interfacial cracks at both ends, followed by transverse cracks within the coating resulting in its ultimate fracturing into segments. Under compressive loading, the damage also initiates at the ends with interfacial cracks and propagates towards the centre until the coating completely peels off. The findings from this research build a solid foundation for estimating the damage of cementitious coatings for trusses and large space structures, as most of the structural components in these structures are axially loaded. This work also provides an effective approach for further research on understanding damage mechanisms in cementitious coatings in steel frame structures under more realistic loading conditions.

* Corresponding author at: College of Civil Engineering, Tongji University, Shanghai 200092, China. Tel.: +86 21 65982975 16.
E-mail address: swchen@tongji.edu.cn (S. Chen).

http://dx.doi.org/10.1016/j.conbuildmat.2015.04.025
0950-0618/

1. Introduction

Building regulations across the world require that in the event of a fire structural systems maintain integrity, insulation and stability over an adequate "length of time". Integrity and insulation refer to the desirability of the fire to be stopped from spreading beyond the compartment of origin, while stability alludes to the necessity of the structure itself to sustain its load-bearing function over the required period.

Because of its high thermal conductivity and rapid reduction of strength and stiffness properties with temperature, steel structures are generally considered to be vulnerable to elevated temperatures such as those occurring under fire conditions. Structural steel loses roughly half its strength and stiffness at 550 °C and over 90% at temperatures above 800 °C. To address this problem the traditional practice has been to insulate steel structural members from the effect of fire for a required period of time. Cementitious fireproofing materials have been widely used as fire protective coatings on steel structures due to their durability, low density, low thermal conductivity, low cost, and non-toxic emissions upon exposure to fire. These coatings are usually made of cement mixed with aggregates such as expanded vermiculite to make them lightweight. The required thickness of cementitious coating is usually applied in-situ to structural steel members as a wet mixture. Because of their unsightly appearance, steel structural members protected in this manner end up hidden under architectural claddings and finishes. This makes it difficult and expensive to monitor the condition of the protective coatings over time or to carry out inspections after moderate or severe loading events (such as windstorms, fires or earthquakes). However, given that these coatings are cementitious and specifically designed to be lightweight, they are naturally fragile and brittle and prone to damage under deformation or vibration [1–3]. It is therefore reasonable to expect a potential reduction in the fire resistance of such buildings [4–7] after a period of use, especially if this period has included one or more of the aforementioned moderate or severe loading events. For instance, in the tragic '911' event, the inadequate and damaged fire protection due to the plane impact was considered to reduce the fire resistance afterwards and therefore contribute to the eventual collapse of the World Trade Centre (WTC) towers [8,9]. Apart from the obviously damaging impact of extreme loads, relatively moderate loads such as impact, wind load or seismic action, may also induce significant monotonic and cyclic deformations in the structure and cause damage to fire protection but with limited external signs of damage. Coating damage may occur over a single significant loading event or be of a cumulative nature leading to progressive deterioration of its integrity and therefore its ability to provide the designed level of fire protection (as illustrated in Fig. 1).

This deterioration represents a hidden danger to the safety of a building and its occupants in the event of a fire. Thus it is imperative to develop methodologies for estimating the in-situ condition of fire protection after a severe loading event or after a relatively long period of service. In order to achieve this goal, the performance and damage mechanisms of cementitious coatings under a variety of simple and complex loadings must be well understood.

So far there has been little formal investigation of the potential fire safety risk posed by damaged cementitious fire protection as even the most fundamental failure mechanisms of such coatings have not been properly quantified, which is key purpose of the research reported in this paper. After the September 11, 2001 event, the adhesive/cohesive strengths of fibre-based spray-applied fire-resistive materials have been investigated [2] as part of WTC collapse investigation. Dwaikat and Kodur [10] present parametric studies conducted for modelling the fracture and delamination of cementitious coating on the insulated steel plates subjected to static and impact loads based on a mixed 2D cohesive zone finite element (CZFE) scheme.

In order to develop a method for evaluating the damage in cementitious coatings on steel members subjected to external loading, fundamental research has been carried out in Tongji University, which includes experiments on the mechanical properties of cementitious materials and adhesion properties of the coating to steel substrate [1,11], interlaminar stress analyses on axially or flexurally loaded steel members [1,11,12], monotonic loading tests on cementitious coated steel members under axial loads and under pure bending [1,11,13,14], and detailed numerical studies [13–15]. In the numerical simulation, a cohesive zone finite element (CZFE) scheme is adopted, which employs a cohesive zone model (CZM) [16–17] in conjunction with contact pair for the interfacial crack propagation and the William-Warnke model [18] for the internal damage within the coating.

This paper presents comprehensive experimental and numerical studies on damage mechanisms in cementitious coatings on steel members under axial loading. First, tests are conducted to obtain the mechanical properties of the cementitious coating to understand the behaviour of the cementitious coating itself and its adhesion to steel substrates. Then, monotonic loading tests are carried out to investigate the damage in cementitious coatings on the coated steel plates subject to pure tension and compression loadings. To analyse the damage, the CZFE scheme is adopted for modelling the tests and validated against the analytical and elastic FE solutions.

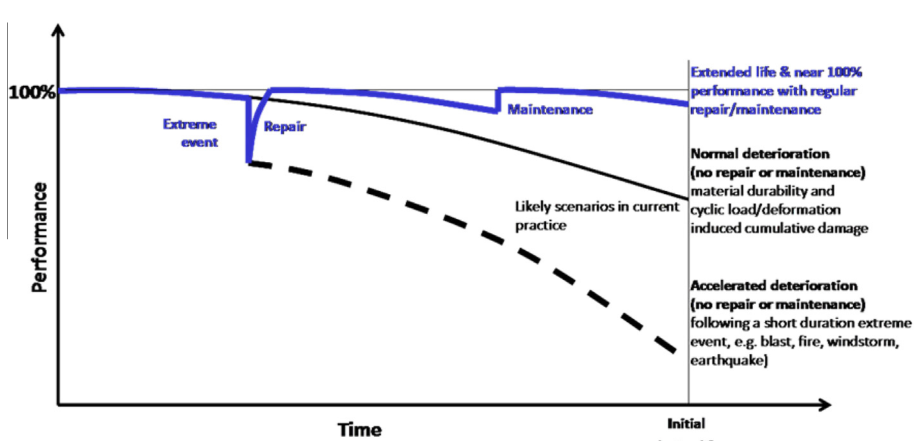

Fig. 1. Performance deterioration of cementitious fire protection over the design life.