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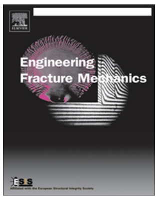

Cohesive zone model properties for evaluating delamination of spray-applied fire-resistive materials from steel structures

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ABSTRACT

This paper presents cohesive zone model (CZM) fracture properties of spray-applied fire-resistive material (SFRM) for modeling delamination of fire insulation from steel structures. For characterizing cohesive zone properties, namely cohesive strength, cohesive fracture energy and cohesive displacement ductility, a set of experiments are conducted on three types of commercially available SFRM namely medium density Portland cement-based, medium density gypsum-based and mineral fiber-based. Data from experiments is utilized to develop a cohesive stress–displacement relationships in both mode-I and mode-II delamination. The recorded stress–displacement relationship indicates noticeable strain-softening zone verifying that SFRM is not a completely brittle material, rather, it is quasi-brittle.

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1. Introduction

Steel is one of the primary materials used in structural framing of buildings due to numerous advantages steel offers such as high strength-to-weight ratio, high level of ductility and ease in fabrication and construction process. However, steel structures, in general, do not exhibit favorable fire-resistance due to high thermal conductivity of steel, slender sectional shapes and rapid deterioration of strength and modulus properties of steel with temperature. Hence, steel structures are to be provided with fire insulation to achieve required fire resistance ratings as specified in building codes. This is often achieved through spray applied fire resistive materials (SFRM) that are externally applied to surface of steel structural members. During extreme loading events such as earthquake, blast and impact, there is a high possibility that active fire protection systems get compromised by ruptured water supply piping system and delayed response for firefighting [41]. In such scenarios, adequate fire resistance of structure is the only line of defense for overcoming the damage or collapse of structural systems. Therefore, fire performance of steel structures relies entirely on the effectiveness of fire insulation applied on structural members.

SFRM is widely used as fire insulation material due to number of advantages it offers over other insulation materials, including low thermal conductivity, light weight, cost-effectiveness and ease of application [37]. The main function of SFRM is to delay the temperature rise in steel, and thus slow down the degradation of stiffness and strength properties of steel when exposed to fires.

Effectiveness of SFRM during fire, following impact or earthquake, entails ensuring stable fracture resistance at steel–SFRM interface such that SFRM would not delaminate during these extreme loading events. However, recent experiences

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Nomenclature

SFRM	spray applied fire resistive materials
CZM	cohesive zone model
FPZ	fracture process zone
LEFM	linear elastic fracture mechanics
CTOD	crack tip opening displacement
DCB	Double Cantilever Beam
ENF	End Notched Flexure
MTS	material testing system
G	fracture energy
σ	cohesive stress
δ	interfacial opening displacement

have shown opposite. For instance, the progressive collapse of WTC twin towers was partially attributed to loss of fire insulation resulting from high impact loads [27,44]. These incidents have led to a major debate with respect to the role of fire insulation on structural integrity and resiliency of high-rise buildings under extreme loading events [44]. Limited experiments have also clearly demonstrated that SFRM does not possess enough fracture toughness to remain intact during cyclic loading [17]. Such delamination or damage to SFRM can strongly jeopardize the fire performance of steel structures [25,30].

For evaluating post-impact or post-earthquake fire performance of steel structures, it is of crucial importance to have comprehensive knowledge regarding the extent of SFRM damage during impact or earthquake loading. However, in current fire safety provisions, owing to lack of adequate knowledge on delamination of SFRM from steel structures, as well as lack of cohesive fracture properties of SFRM, the effect of extreme loading events, such as fire following earthquake or impact, on fire performance of steel structures, is not addressed. This serious shortcoming in current provisions necessitates developing a robust approach to predict the delamination of SFRM from steel structures. Developing such knowledge is one of the imperative steps towards rational design and assessment of post-impact and post-earthquake fire performance of steel structures.

Fracture mechanics and Cohesive Zone Model (CZM) approach has proven to be a powerful tool for simulating delamination in composites and adhesive joints [19,7]. Also, Alfano et al. [8,10] used a potential-based CZM to simulate debonding in Al/epoxy T-peel joints. A fundamental step associated with the application of CZM technique is determination of CZM constitutive parameters, namely cohesive strength, cohesive fracture energy and shape of traction–separation law. A new method was assessed by Alfano et al. [9] to identify CZM in which finite element simulations and full field kinematic data are combined. However, there is limited data in literature on the cohesive zone properties of SFRM for modeling the delamination of SFRM from steel structures.

This paper presents cohesive zone model (CZM) fracture properties of spray-applied fire-resistive material (SFRM) for modeling delamination of fire insulation from steel structures. To develop the cohesive zone properties for three types of commercially available SFRM, a series of material property tests is carried out. The cohesive parameters are evaluated for both normal and shear modes, namely mode-I and mode-II fracture. Subsequently, a fracture mechanics-based numerical approach incorporating CZM [36] is used to simulate the conducted tests in which the cohesive laws, developed using experimental data, are implemented.

2. Fracture mechanics of SFRM

Spray-applied fire-resistive material (SFRM) is commercially available in cementitious and mineral-fiber-based forms. Cementitious-based SFRM is further grouped under two categories; gypsum-based SFRM that comprises gypsum and vermiculite, and Portland-cement based SFRM that is composed of Portland cement and vermiculite. Mineral-fiber-based fire insulation comprises of Portland cement and mineral wool fiber mixture. Cementitious and mineral-fiber-based SFRM are delivered to the construction site as wet-mix and dry-mix, respectively. Performance of SFRM during extreme loading conditions is highly dependent upon its integrity, constitutive ingredients, and the manner in which insulation is prepared and applied to the steel surface. During application of SFRM on steel structural members, microscopic cracks can develop within bulk SFRM itself, and also at the interface between steel and SFRM, mainly due to high shrinkage and low tensile strength of SFRM. With increase in loading, that can occur under extreme loading conditions steel structures undergo high level of deformations. Consequently, existing microcracks within SFRM can widen and propagate to the steel–SFRM interface leading to partial or full delamination of fire insulation.

Cementitious materials can be considered as two-phase composites comprising of a homogeneous phase and a particle phase [42]. Hence, in cementitious SFRM, the matrix is composed of hydrated cement gels or gypsum paste and the vermiculite particles form the reinforcement. This way the fracture properties of SFRM can be taken to be the average of individual properties of the two phases and the interfacial bond between the phases [21]. Given the fact that cement or gypsum

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