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Effective properties of spray-applied fire-resistive material for resistance to cracking and delamination from steel structures

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HIGHLIGHTS

- Factors governing delamination of SFRM from steel structures are evaluated.
- Cohesive zone model is applied to simulate delamination phenomenon.
- Delamination of fire insulation from steel truss is modeled.
- Delamination of fire insulation applied on a beam-column assembly is modeled.
- Effective properties of SFRM to mitigate delamination are quantified.

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ABSTRACT

This paper presents a study on quantifying the effective properties of spray-applied fire-resistive material (SFRM) to mitigate delamination of fire insulation from steel structures. The crack development in SFRM, its propagation and then delamination is investigated for two types of structural elements; a flimsy steel truss chord, and a beam-column assembly in a moment-resisting frame insulated with three types of SFRM widely utilized in steel construction. In the truss chord, the strain ductility of steel at which delamination initiates and propagates is studied, while in the beam-column assembly, the extent of delamination over the plastic hinge region developed on the beam is monitored. A fracture mechanics-based numerical model is employed to undertake parametric studies to determine effective parameters of SFRM for minimizing delamination. In the sensitivity study, the material properties of SFRM applied on steel members are varied over a wide range. Results from the sensitivity study indicate that the elastic modulus of fire insulation (E), thickness of insulation (t) and interfacial fracture energy (G_c) are the crucial factors that govern the delamination of SFRM from the steel surface. Subsequently, results from an additional set of parametric studies, carried out on a beam-column assembly, also infer that delamination of SFRM occurs over the plastic hinge region and is mainly governed by the critical factors of E, t and G_c. Results from these studies indicate that all three governing factors play a critical role in determining the extent of delamination and such delamination can be overcome if the interface fracture energy in normal mode is enhanced to 350 J/m^2.

1. Introduction

Steel structures do not exhibit good fire-resistance due to high thermal conductivity of steel and rapid deterioration of strength and stiffness properties of steel with temperature. Hence, steel structures are to be provided with fire insulation to achieve required fire resistance. This is often achieved through spray applied fire resistive materials (SFRM) that are externally applied on the steel surface. SFRM is widely used as a fire insulation material due to the number of advantages it offers over other insulation materials. These include low thermal conductivity, light weight, cost-effectiveness and ease of application [20]. The main function of SFRM in a steel structure is to delay the temperature rise in steel, and thus slow down the degradation of stiffness and strength properties of steel when exposed to fire.

According to past experiences, a destructive fire can develop either as a primary event or as a secondary event following an earthquake [25], impact and blast [26] in building structures, as well as in petrochemical facilities and offshore structures [28]. During the occurrence of fire following an earthquake, blast or impact, there is a high probability that active fire protection

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systems get compromised by ruptured water supply piping systems and delayed response for firefighting. In such scenarios, adequate fire resistance is the only line of defense for overcoming the damage or collapse of structural systems. Therefore, there is a great concern with respect to reliability and effectiveness of SFRM during fire following the above loading scenarios.

The role of SFRM, as a protective layer during fire following above extreme loading conditions, can be compromised if the energy transferred to the structure by seismic, impact and blast loading, can cause fracture and delamination of fire insulation from the steel surface. This hypothesis has been addressed by previous experiments and field observations [8,33,26]. Under this type of loading, dynamic interfacial stresses developed at the SFRM–steel interface in the highly stressed zones of structural elements can open the cracks that are inevitably left over from the SFRM application process. Once initiated, theses cracks can rapidly propagate along the interface of steel and SFRM leading to delamination of SFRM from the steel surface. The extent of fire insulation loss depends on the load severity and fire insulation resistance against fracture and delamination.

The key question raised in some of the recent studies is whether the SFRM types, currently used in steel construction, possess enough fracture toughness to resist fracture and delamination under the action of seismic, impact and blast loading [17]. Further, if the current SFRM types are vulnerable and hence can be dislodged from the steel surface, what types of material properties would be required to avoid the delamination of fire insulation from the surface of steel structures. Owing to the lack of answers to the above questions, current fire safety provisions do not fully take into consideration the effect of such insulation damage on the fire resistance of structures during fire following earthquake, impact and blast.

The most effective way of minimizing delamination of SFRM applied as fire insulation on steel structures is to enhance the fracture properties of SFRM. This requires characterizing the fracture properties of currently available SFRM and to determine key fracture properties that influence delamination. A review of literature indicates that Braxtan and Pessiki [7] through strength-based tests, Tan et al. [30] through indirect fracture tests, and Kodur and Arablouei [19] through direct fracture tests have established the fracture properties for different types of currently available SFRM. However, there is lack of data on the critical factors governing the delamination phenomenon for structural elements or configurations and further on the key fracture properties that can prevent delamination of SFRM from steel structural elements.

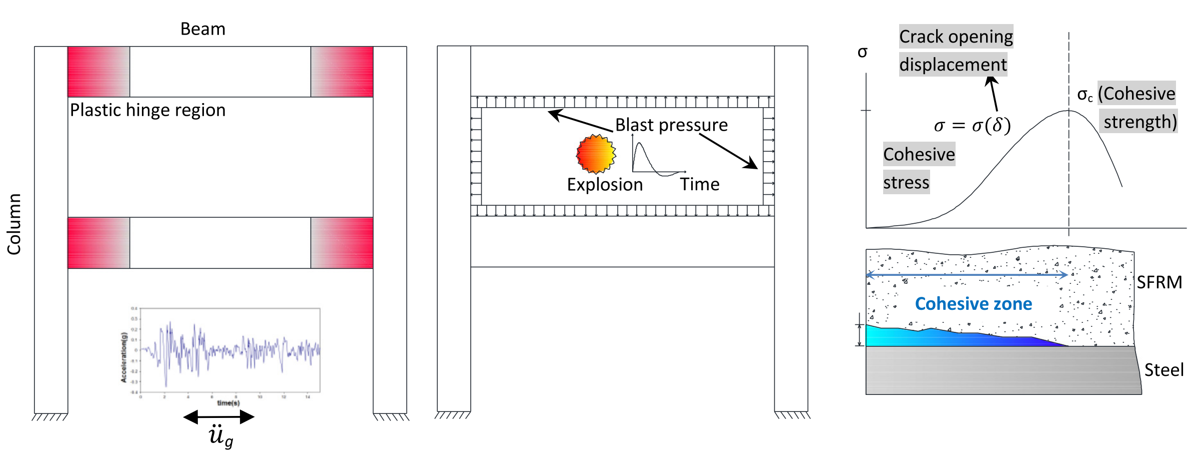
In this study, a fracture mechanics-based numerical approach is adopted to first identify critical factors governing the delamination of fire insulation from steel surface. This is undertaken by modeling delamination of SFRM from slender members such as a steel truss chord subjected to tensile deformation. Subsequently, the level of critical fracture energy required to prevent delamination of fire insulation from a beam-column assembly subjected to seismic loading is quantified. In the numerical model, the extent of delamination over the plastic hinge developed at the beam is monitored as a function of the critical factors governing delamination; thereby the fracture properties required for mitigating delamination are quantified.

2. Mechanism governing fracture of SFRM

Spray applied fire resistive materials (SFRM) are commercially available in cementitious and mineral fiber-based forms. Cementitious-based SFRM is further grouped under two categories; gypsum-based SFRM that comprises of 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.

Cementitious materials can be considered as two-phase composites comprising of a homogeneous phase and a particle phase [24]. 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 the individual properties of the two phases and the interfacial bond between the phases [10]. Given the fact that cement or gypsum constitutes nearly 70% of SFRM, both of which are cementitious materials, static and dynamic fracture mechanics of SFRM is expected to be analogous to the one developed for a cementitious material.

When steel structures are subjected to seismic, blast or impact loading, as shown in Fig. 1a and b, partial or complete delamination of fire insulation (SFRM) from beams and columns can occur. Under such loading scenarios, illustrated in Fig. 1a and b, cracking in insulation can develop, leading to its delamination from the steel surface as illustrated in Fig. 1c. This crack initiation and propagation phenomenon can be explained using fracture mechanics principles developed for cementitious materials [10]. Fig. 1c depicts the typical vicinity of a crack at the steel–SFRM interface and the associated fracture process zone (FPZ) developed



a) Frame subjected to strong ground motion b) Frame subjected to blast over pressure c) Crack development at steel-SFRM interface

Fig. 1. Progression of crack at the interface of steel and SFRM during extreme loading conditions on steel moment-resisting frame (based on cohesive zone model concept).