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A fracture mechanics-based approach for quantifying delamination of spray-applied fire-resistive insulation from steel moment-resisting frame subjected to seismic loading

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A B S T R A C T

This article presents a numerical approach based on fracture mechanics theory for evaluating crack initiation, propagation, and delamination of fire insulation at the interface of spray-applied fire insulation and steel surface of a moment resisting frame under the action of earthquake loading. Progression of delamination at the fire insulation-steel interface during cyclic loading is simulated through contact interaction analysis in which Cohesive Zone Model is adopted to model the interface damage and softening. The developed 3D finite element model is validated by comparing predictions from the model, namely crack initiation, crack propagation pattern and the extent of delamination of insulation, against test data generated both at material and structural levels. The validated model is applied to quantify the effect of cyclic damage accumulation at SFRM-steel interface through a parametric study in terms of interfacial critical fracture energy. The influence of local buckling occurring in flange on the extent of delamination is considered in the analysis. Results from the parametric studies indicate that critical fracture energy at steel-insulation interface has significant influence on the extent of damage accumulation over the plastic hinge zone. Further, flange local buckling can substantially enhance the development of tensile stresses at the crack tip leading to delamination over a larger surface area.

1. Introduction

Fire following an earthquake is one of the possible scenarios to be accounted for in the design of structural systems [18]. Post-earthquake fire consideration therefore has been drawing attention over the few past years as a part of an emerging trend towards enhancing structural resiliency under multi-hazard scenarios. Substantial inelastic actions in structures during an earthquake can impose large deformation in structural and non-structural elements. Also, devastating fire can be triggered by ruptured gas line, damaged electrical wiring or falling candles etc. In such a scenario, there is a high possibility that active fire protection systems can also be compromised by ruptured water supply piping system and delayed response for firefighting [18]. In such scenarios, adequate fire resistance of structure is the only line of defense for overcoming the damage or collapse of structural systems. In steel structures the fire resistance is mainly dependent on the adherence of fire insulation to structural members. A review of literature clearly shows that post-earthquake fires caused numerous fatalities and

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Nomenclature

SFRM	spray applied fire resistive materials
R	response modification factor
CZM	Cohesive Zone Model
WM	wet-mix (SFRM)
DM	dry-mix (SFRM)
G	fracture energy

high fire losses in many previous earthquakes. As an example, in the aftermath of Hyougoken-Nambu earthquake (Kobe, Japan, 1995) 7000 buildings were destroyed by post-earthquake fires alone [12].

Steel moment-resisting frames are quite frequently used in earthquake prone regions due to their superior seismic resistance mainly because of high ductility level they offer. However, steel structures in general do not exhibit favorable fire-resistance due to high thermal conductivity of steel and rapid deterioration of strength and modulus properties of steel with temperature. Hence, steel moment frames 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 to steel surface. 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 post-earthquake fire.

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 [17]. In order for SFRM to be effective as a protective layer during post-earthquake fire, it requires to remain adhered to steel throughout the strong ground motions. However, one of the main disadvantages of spray-on protective materials is that they are often fragile (brittle) and can be susceptible to damage under the action of earthquake loads [6]. Under this type of loading, cyclic interfacial stresses developed at the SFRM-steel interface in the highly stressed zones of structural elements could open the cracks that are inevitably left over from SFRM application process. Theses cracks then propagate during subsequent loading cycles and this can lead to delamination of SFRM from steel surface.

In current practice, it is assumed that SFRM will not delaminate or disintegrate under cyclic loads and will continue to maintain its integrity during post-earthquake fires. Owing to lack of sufficient knowledge on this topic, current fire safety provisions do not address the effect of multiple hazards such as fire following earthquake on fire resistance of structures. In the fire resistance analysis, thermal response of steel structures is evaluated by assuming SFRM to be perfectly intact during a post-earthquake fire. However, limited experiments have clearly shown that SFRM delaminates under high levels of cyclic loading [6]. Such delamination or damage to SFRM can jeopardize the performance of steel moment frames subjected to post-earthquake fire exposure. Therefore, developing a fundamental understanding on crack propagation mechanism and causes for delamination at SFRM-steel member interface is extremely crucial from structural fire performance standpoint. Recent post-earthquake fires and poor fire performance of steel structures have spawned concerns regarding the reliability of fire insulation effectiveness and consequently the response of structure under post-earthquake fire [12]. Nevertheless, there are very limited studies on this topic and thus there is no clear understanding on the propagation of damage and delamination in fire insulation during cyclic earthquake loading.

To develop an understanding on the process of delamination of fire insulation from a steel moment frame, a numerical model is developed for evaluating interfacial fracture and delamination of fire insulation from steel surface during an earthquake loading. Contact interaction analysis is carried out and a Cohesive Zone Model (CZM) is employed as material constitutive model for interface in a 3D finite element model to simulate initiation and propagation of cracks at SFRM-steel interface throughout the earthquake loading. The model is applied to undertake a parametric study to quantify critical factors influencing the delamination phenomenon.

2. Insulation delamination phenomenon during earthquake

The fire resistive performance of fire insulation is highly dependent on its integrity, the constitutive ingredients, the manner in which insulation is prepared and applied to the steel surface, and the extreme loading conditions encountered by the structural member during its service life. Typically SFRM is available in cementitious and mineral-fiber-based forms. In practice, cementitious-based SFRM is divided into two categories; gypsum-based material that comprises of gypsum and vermiculite, and Portland-cement based material that comprises of Portland cement and vermiculite, both of which are delivered to the construction site as wet-mix. Mineral-fiber-based insulation material comprises of Portland cement and mineral wool fiber mixture and is delivered to the construction site as dry-mix. The components in both types of SFRM make it very fragile which is regarded as one of the weak points of this type of fire insulation [5].

Special steel moment-resisting frames, which have gained vast attention in earthquake prone regions, are assigned the highest response modification factor (R) [19] and thus are expected to experience very large deformations. In steel moment frames subjected to earthquake loading, as shown in Fig. 1, plastic hinges are formed in beams at the vicinity of columns, as