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Effect of fire insulation delamination on structural performance of steel structures during fire following an earthquake or an explosion

Amir Arablouei [a], Venkatesh Kodur [b,*]

[a] Technip USA, Inc., Houston, TX, United States
[b] Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI, United States

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ABSTRACT

In this article a numerical model is presented for simulating fire performance of steel structures following an earthquake or an explosion event. In particular, effect of fire insulation delamination during seismic and blast loading on fire performance of structural members is studied. The extent of delamination of fire insulation over the structural elements is adopted from previous fracture mechanics-based studies. A sequential thermal-structural analysis is carried out to trace the fire performance of beam-column assembly in a moment-resisting frame and a beam-column member supporting heavy axial loads. Results from the analyses clearly show that consequence of delamination of fire insulation from plastic hinge region developed in the beam near the column can be quite substantial.As such, 25% delamination of fire insulation can reduce failure time from 100 min to 64 min. The lack of full fire insulation over this region can significantly accelerate the progressive collapse of the moment-resisting frame due to development of flexural and shear failure in beams adjacent to columns. Also, results from post-explosion fire analysis demonstrate that detachment of fire insulation from a steel column under blast overpressure can significantly impair structural stability of columns during fire following blast.The beam-column that undergoes fire insulation delamination up to 25%, experiences earlier loss of capacity around 85 min as compared to 120 min achieved in case of no delamination of fire insulation.

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1. Introduction

Fire can accidently occur in structures or following an extreme loading event such as earthquake or an explosion. Post-earthquake fires caused numerous fatalities and 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 [8]. Also, accidental explosions striking petrochemical facilities and offshore platforms are usually followed by a destructive fire. Further, explosions caused by terrorist attacks and ensuing fire pose a serious threat to important federal buildings and also high-rise buildings. For instance, the combined effects of impact or blast and ensuing fire could lead to the progressive failure of structure as in the case the terrorist attack on the World Trade Center buildings [14] or collapse of Piper Alpha platform in North Sea [15].

To maintain stability and integrity of steel structures during fire, 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 surface of steel member [12]. 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 fire. However, substantial inelastic actions in structures during an earthquake or anexplosion can impose large deformation in structural and non-structural elements. During such extreme loading events, there is therefore a high possibility that active fire protection systems get compromised by ruptured water supply piping system and delayed response for fire fighting [13]. Hence, fire insulation applied on structural members will play an important role in preventing excessive temperature development in the steel members during fire.

The critical role of fire insulation during fire following an earthquake or anexplosion can be compromised if the fire insulation gets detached from steel surface. Both experiments and field observations have shown that SFRM can delaminate under static and dynamic loading [3,7,18]. [16,17] investigated the reduction in the fire resistance of steel columns due to the loss of SFRM directly on the column using 2D and 3D thermal analysis, respectively. No structural analysis was performed; instead, the average steel temperature over the cross section was used to determine the time to failure of the columns based on the criteria

* Corresponding author.
E-mail address: kodur@egr.msu.edu (V. Kodur).

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outlined in [6]. Their results showed that insulation loss, though to a very small extent, can significantly influence the fire resistance of a steel column. Kwon et al. [9] investigated the effect of SFRM removal from both web and flange of a steel column by conducting thermal and structural analysis. Based on their numerical results, they concluded that the loss of even small amount of SFRM caused a reduction in strength of the column.

Keller and Pessiki [10] conducted an analytical case study to evaluate the effect of SFRM delamination patterns observed in experiments carried out by [7] on thermo-mechanical response of interior steel moment beam-column assembly during post-earthquake compartment fire exposure. They concluded that significant temperature-induced softening occurs in moment-rotation response of beam-column connection, and as a consequence, flexibility of the structural system for sideway motion is increased resulting in intensified drift demands under the action of residual post-earthquake destabilizing forces.

In previous studies, the extent and location of fire insulation damage in steel members were chosen arbitrarily or based on one set of experiment.This is mainly due to lack of enough understating on the mechanisms of delamination of fire insulation from steel structures. To overcome this knowledge gap, mechanisms of fracture and delamination of fire insulation from steel structures was investigated using an experimental-numerical approach based on fracture mechanics. Using this approach, the extent of delamination over the structural members under seismic and blast loading was quantified [2,5]. Additional details of the fracture mechanics-based study are provided in the next section. In this paper, the effect of fire insulation delamination resulting from an earthquake or an explosion event on subsequent fire resistance of steel structures is quantified. The extent and location of fire insulation delamination is chosen based on the previous fracture mechanics-based studies [2,5].

In this paper, a numerical study is presented in which the consequences of loss of fire insulation from steel structures during fire following an earthquake or explosion are studied. Two sets of analyses are performed; in the first set the consequence of loss of fire insulation from a beam near the column during seismic loading is investigated, and in the second set of analysis effect of fire insulation delamination from a beam-column subjected to blast loading is studied. A sequential thermal–structural analysis is carried out using ANSYS program to compute the temperature time-history developed in the insulated beam and column during exposure to fire and its effect on structural softening and global and local behavior of structural elements. In particular, the time to failure of a moment frame and a beam-column during fire following an earthquake or an explosion, respectively, are quantified.

2. Approach to evaluate delamination of spray-applied fire-resistive material

Under seismic and blast 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 SFRM application process. Once initiated, theses cracks can rapidly propagate along the interface of steel and SFRM leading to delamination of SFRM from steel surface. To evaluate delamination of fire insulation from steel structures a fracture mechanics-based approach was developed in which cohesive zone model concept is adopted to model crack initiation and propagation at the interface of steel and fire insulation [4]. The developed numerical model was utilized to quantify critical factors governing delamination of fire insulation from steel structures and eventually define a characteristic parameter that can incorporate the critical factors. Further, the extent of delamination was quantified

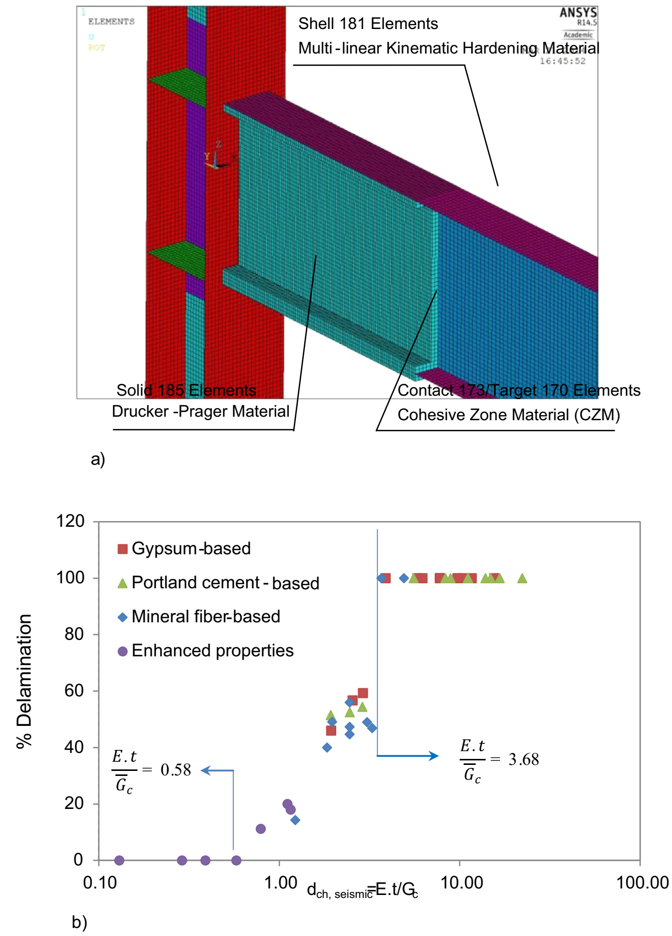

Fig. 1. Approach for studying delamination of fire insulation from a beam-column assembly subjected to seismic loading.

and related to a delamination characteristic parameter under seismic and blast loading conditions.

Results from the analyses clearly indicates that under the action of seismic loading, elastic modulus of SFRM, thickness of SFRM and fracture energy of SFRM are the most influential parameters that govern the mechanics and extent of delamination of fire insulation from a moment-resisting frame [11]. Fig. 1 shows the numerical model and the extent of delamination over the bottom flange of the beam near the column in a moment-resisting frame as a function of delamination characteristic parameter, $d_{ch,seismic}=Et/G_c$(E: elastic modulus, t: thickness, G_c: fracture energy) [11]. As is represented in $d_{ch,seismic}$, the extent of delamination is increased by increasing elastic modulus and thickness of SFRM, while it diminishes when fracture energy of SFRM is boosted. Fig. 1 shows the extent of delamination as a function of parameter $d_{ch,seismic}$for three types of SFRM commonly utilized in practice along with an artificial material with enhanced properties. The fracture energy of the fire insulation should be enhanced to 350 J/m^2 in order to prevent delamination, i.e. parameter $d_{ch,seismic}$should be less than 0.58, as shown in Fig. 1.

Under blast loading condition, delamination of three types of fire insulation from a beam-column was modeled as shown inFig. 2. The extent of delamination is also plotted against the delamination characteristic parameter, $d_{ch,blast}=tP_r/EG_c$ (E: elastic modulus, t: thickness, G_c: fracture energy, P_r: blast overpressure) in Fig. 2 [11]. As is clear, an additional parameter, namely blast pressure,adds to the list of critical factors governing delamination. The extent of delamination has a direct relationship with thickness of SFRM and blast overpressure, whereas it has inverse

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