Engineering Structures 116 (2016) 56–69

Contents lists available at ScienceDirect

Engineering Structures

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

# Modeling delamination of fire insulation from steel structures subjected to blast loading

Amir Arablouei, Venkatesh Kodur *

*Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI, United States*

ARTICLE INFO

*Article history:*
Received 13 July 2015
Revised 22 January 2016
Accepted 23 February 2016
Available online 8 March 2016

*Keywords:*
Blast load
Delamination
Cohesive zone model
Fracture energy
Steel beam–column

ABSTRACT

This article presents a fracture mechanics-based numerical approach for quantifying delamination of spray-applied fire-resistive material (SFRM) from a steel beam–column subjected to a blast loading. In the numerical model, cohesive zone model is employed to simulate interfacial crack initiation and propagating at the interface of SFRM and steel. Three types of SFRM, widely utilized in the practice namely, mineral fiber-based, gypsum-based and Portland cement-based SFRM are considered in the analysis. The numerical model is validated against two sets of experiments; a full scale blast test on a steel beam–column and a drop mass impact test on a steel beam insulated with SFRM. The verified numerical model is subsequently utilized to carry out extensive parametric study to quantify critical factors that can influence the extent of delamination of SFRM from a steel beam–column, namely fracture energy at steel-SFRM interface, elastic modulus of SFRM, thickness of SFRM, and the level of blast overpressure. Results from parametric studies show that Portland cement-based SFRM can provide the highest level of resiliency in terms of withstanding the applied blast overpressure, while mineral fiber-based SFRM shows the lowest level of endurance. Further, the outcomes obtained from parametric study demonstrate that the extent of delamination can directly be related to blast overpressure and thickness of SFRM, whereas it can inversely be related to elastic modulus and fracture energy of SFRM. Based on the results of parametric study, a delamination characteristic parameter, which incorporates the major factors influencing the delamination, is defined and the extent of delamination is expressed as a function of this parameter.

## 1. Introduction

To protect public, environment, and assets and facilities against accidental explosions, blast loading has been increasingly appearing as a loading scenario to be considered in the design of critical infrastructure. An explosion event can be either hydrocarbon-driven, as in the case of offshore platforms and refineries, or explosives-driven as in the case of bomb attack on infrastructure. Both types of explosions can be followed by a destructive fire whose ramifications may even be more adverse than the blast loading itself. The collapse of the Alfred P. Murrah federal building [13] as a target of terrorist bombing has raised a great concern regarding blast resistance of federal buildings. Further, the tragic progressive collapse of World Trade Center buildings [32] and destruction of Piper Alpha platform in North Sea [33] was attributed to the combined effect of blast and fire. Nevertheless, the blast-fire interaction effects on structural behavior have not yet been well-understood.

Steel structures, which are quite popular in high-rise buildings, bridges, offshore structures, and petrochemical facilities, do not exhibit good fire-resistance. The high thermal conductivity of steel and rapid deterioration of its strength and stiffness properties with temperature, is mainly responsible for this shortcoming. Therefore, steel structures are to be provided with fire insulation to achieve required fire resistance and maintain integrity during fire. This is often achieved through spray applied fire resistive materials (SFRM) that are externally applied on steel surface. 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 [26]. 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. During explosion, there is a high possibility that active fire protection systems get compromised by ruptured water supply piping system and delayed response for firefighting. In such scenarios, adequate fire resistance of structure is therefore the only line of defense for overcoming the damage or collapse of structural systems.

---

* Corresponding author. Tel.: +1 (517) 353 9813; fax: +1 (517) 432 1827.
*E-mail address:* kodur@egr.msu.edu (V. Kodur).

http://dx.doi.org/10.1016/j.engstruct.2016.02.042
0141-0296/

Given the above explained critical role of fire insulation in maintaining the integrity of steel structures during fire following blast, a key question that may quiz the owners and the structural engineering community is whether the applied fire insulation on the steel structures would survive the blast overpressure directly targeting the fire insulation applied on the steel members. In fact, if the fire insulation would not remain in-place during blast, steel structural elements would have to face the subsequent fire without any protection. Providing a deterministic answer to the above question is impossible until experimental and numerical researches are conducted to simulate this phenomenon. However, results from other studies show that SFRM can crack and delaminate from the steel surface under seismic and impact loading scenarios [9,38,32,1]. These outcomes infer that fire insulation can be vulnerable under the action of blast overpressure.

Beam–columns in high-rise buildings are primary load-bearing members of a structural system and failure of these members may impose significant threat to the occupants, and in worst-case scenario, can lead to progressive collapse of the structure. Loss of fire insulation on these beam–columns during blast loading can leave theses members partially or fully exposed to high temperature. Results of fire resistance analysis carried out on a W14X145 steel column [12] showed that 5% loss of insulation can lead to 50% reduction in plastic capacity of column. The direct exposure of column to elevated temperatures along with the horizontal pull-in forces exerted on steel columns due to sagging and centenary action of beam or truss system (as a consequence of fire) can push the columns to a critical point where they develop viscoplastic global buckling and are no longer able to support the weight of the above stories. The catastrophic collapse of World Trade Center buildings proved that the consequence of loss of fire insulation from steel beam–columns can be quite tremendous and irreversible [8,32].

The fire resistance assessment of steel structures during fire following blast entails a broad understanding with respect to endurance of fire insulation under the action of blast waves. Nonetheless, there is no research data in the open literature, on addressing this critical issue. Due to lack of such data and knowledge on this topic, the current practice is not able to account for chain events arising from multi hazard scenarios, such as blast and subsequent fire. This study aims to address this problem through carrying out dynamic numerical simulations in which the blast performance of a steel beam–column insulated with fire insulation is evaluated. A particular attention is devoted toward modeling the cohesive failure and interfacial fracture of fire insulation under the action of blast pressure. A fracture mechanics-based numerical approach is adopted to simulate crack initiation and propagation at the interface of fire insulation and steel beam–column subjected to blast overpressure. The cohesive failure of bulk fire insulation is also modeled by utilizing a plasticity-based constitutive model. A numerical model, developed in LS-DYNA computer program (2014), is employed to perform a set of parametric study to quantify the effect of governing factors on the extent of cracking and delamination of fire insulation from a steel beam–column.

## 2. Delamination of fire insulation during blast loading

Any rapid release of energy, either as a consequence of detonation of an explosive charge at a stand-off position from a building, or ignition of a vapor cloud on an offshore platform, can generate a high pressure shock wave that travels at a velocity faster than the speed of sound. When a steel beam–column is encapsulated with fire insulation, the blast wave first attacks the fire insulation standing in front the blast wave. The applied pressure subsequently gets transferred to the web and flanges of beam–column and causes lateral deformation in beam–column. During this process the bulk fire insulation undergoes internal demands that can exceed the weak cohesive resistance of the fire insulation material. In addition, the interface between steel and SFRM can develop interfacial stresses as a result of two phenomena; stress waves being transferred to beam–column, and relative deformation of steel and fire insulation due to deformation of beam–column under applied blast loading. Provided the interfacial demands exceed the bonding strength of the interface, SFRM can delaminate from the steel surface. In order to properly evaluate the performance of fire insulation under blast loading, the delamination process is modeled using principles of fracture mechanics in this paper.

Two common forms of commercially available SFRM that are widely used in steel structures are cementitious-based and mineral fiber-based SFRM. Cementitious-based SFRM is further categorized as 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 materials can be considered as two-phase composites comprising of a homogeneous phase and a particle phase [29]. Hence, in cementitious SFRM, the matrix (homogeneous phase) is composed of hydrated cement gels or gypsum paste and the vermiculite particles (particle phase) 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 [10]. Owing to the fact that cement or gypsum constitutes nearly 70% of SFRM, both of which are cementitious materials, the fracture mechanics principles developed for cementitious materials [10] can be adopted to study dynamic fracture (i.e. crack initiation and propagation) in SFRM applied on members subjected to blast pressure.

Fig. 1a illustrates an internal explosion in a building frame that can generate a blast overpressure applied on a beam–column supporting weight of the above stories. The blast overpressure time-history depicted in Fig. 1b can lead to cracking and delamination of SFRM from steel surface as illustrated in Fig. 1c and d. The applied pressure compresses the SFRM causing cohesive failure and fracture within the SFRM in the vicinity of the flange tips. Subsequently, the pressure wave is transferred through SFRM to steel surface. The pressure applied on the SFRM covering web and flange tips of the beam–column imposes compression stresses on the steel-SFRM interface, while the pressure applied on the SFRM covering flanges of beam–column causes tensile and shear stresses at the interface of SFRM and steel. The stresses developed at the interface of steel and SFRM can initiate an interfacial crack and propagation of that crack can lead to complete delamination of fire insulation from steel surface within milliseconds. Fig. 1d depicts a typical crack propagation at the vicinity of steel-SFRM interface and associated fracture process zone (FPZ) developed at the crack tip. Within the FPZ, microcracking and debonding between the cement/gypsum and the aggregates/mineral fibers occurs causing strain-softening behavior in this zone. Delamination is initiated when the cohesive stress ($\sigma$) at the SFRM-steel interface reaches cohesive strength ($\sigma_c$) and subsequently progresses until the cohesive stress reaches zero value. At this point, delamination is completed which means, released fracture energy ($G$) reaches to critical interfacial fracture energy ($G_c$). As shown in Fig. 1e and d, during fire following explosion the flange of beam–column will get exposed to high temperature as a consequence of delamination of SFRM.

The fracture and delamination of fire insulation from steel structures has not been well established as there is limited research available in the literature on this topic. In particular, there is not a single research, neither numerical nor experimental, on the effect of blast loading on the integrity of SFRM applied on the steel