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.

Keywords: Cohesive zone model, Cohesive strength, Fracture energy, Displacement ductility, Delamination

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 (Mousavi et al. 2008). 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 (Kodur and Shakya, 2013). 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 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 (FEMA 2002, NIST 2005). 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 (NIST, 2005). Limited experiments have also clearly demonstrated that SFRM does not possess enough fracture toughness to remain intact during cyclic loading (Braxtan, Pessiki 2011b). Such delamination or damage to SFRM can strongly jeopardize the fire performance of steel structures (Gu and Kodur, 2011).

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 (Camanho et al., 2003; Alfano et al., 2009). Also, Alfano et al. (2011) 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. (2015) 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 (Kodur and Arablouei, 2013) 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 (Modeer, 1979). 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 (Cotterell and Mai, 1996). Given the fact that cement or gypsum constitutes nearly 70 percent of SFRM, both of which are cementitious materials, the fracture mechanics

of SFRM is expected to be analogous to the one developed for a cementitious material. Considering the extensive amount of research (Cotterell and Mai, 1996) on the application of fracture mechanics for cementitious material such as cement paste and concrete, postulated fundamental principles can provide worthwhile direction for comprehending the delamination phenomenon in SFRM based on fracture mechanics principles.

Fig. 1 illustrates a typical vicinity of crack in cementitious material and associated fracture process zone (FPZ) developed at the crack tip. Within the FPZ, microcracking and debonding between the cement and the aggregates occurs causing strain-softening behavior in this zone. In fact, the size of the FPZ plays a crucial role in the application of fracture mechanics principles for cementitious materials. The size of fully developed FPZ in cementitious materials is usually large. For instance, cement paste has FPZ size in the order of a millimeter (Higgins and Bailey, 1976), and the FPZ in mortar is around 30 mm (Hu and Wittmann, 1989). Although cementitious materials behave elastic outside the FPZ, application of classical linear elastic fracture mechanics (LEFM) theory, which is based on single parameter namely stress intensity factor, is highly suspicious owing to large size of localized FPZ at crack tips. In addition, application of LEFM theory entails assuming the location of initial crack, as well as crack propagation path, which makes computational process cumbersome and unmanageable, especially in 3D problems.

As a more rigorous alternative, Cohesive Zone Model (CZM) approach can be adopted to tackle the effect of FPZ size on fracture process in materials (Dugdale, 1960 and Barenblatt, 1962). In fact, it was first proposed by Dugdale (1960) to lump the plastic zone at crack tip into a narrow band along which the crack faces are subjected to constant stress (steel yield stress). This idealization was later generalized to many other fracture processes where debonding can be localized in a strip-shaped process zone which is called cohesive zone. This cohesive zone, shown in Fig 2b, is characterized by cohesive stresses binding crack faces which are dependent on separation distance between crack faces. Cohesive law, which is material-specific, expresses the relation between traction and separation over the cohesive zone. CZM approach has successfully been applied for characterizing fracture in ductile metals, fiber reinforced

composite materials, ceramics, concretes, and also for evaluating interfacial delamination between materials (Camanho et al., 2003; Scheider and Brocks, 2006; Turon et al., 2006; Park et al., 2008; Alfano et al., 2009). Application of this technique for modeling delamination between SFRM and steel will comprehensively be explained in subsequent sections.

A review of literature indicates that there have been limited studies, both at material and structural levels, on delamination and fracture of fire insulation from steel structures. At material level, Chen et al. (2010) carried out tests to evaluate mechanical and interfacial properties of SFRM, including compressive strength, tensile strength, normal bonding strength and shear bonding strength. However, they did not measure load-displacement response of SFRM-steel interface and reported only maximum strength attained at fracture. Braxtan and Pessiki (2011a) evaluated bond strength of both wet-mix and dry-mix SFRM through tests on small scale steel coupons. They also studied the effect of surface mill finish of steel on bond performance. Based on these tests they reported that the bond strength is three times higher for wet mix than that for dry mix, and mill finish can considerably degrade adhesion strength between dry mix SFRM and steel. However, they did not provide any load-displacement response at SFRM-steel interface. These tests, obviously, do not provide needed material data for studying fracture mechanics of SFRM thoroughly. Tan et al. (2011) proposed a test method for measuring adhesion of SFRM on steel, which is based on LEFM approach and assumes pre-existing cracks at the SFRM-steel interface. Tan et al. (2011) conducted a set of experiments on thin steel plates insulated with thick SFRM. While holding the SFRM in-place, the end of steel coupon was peeled off with a constant displacement rate and the corresponding applied load was measured. However, this test only measures the fracture energy in mode-I fracture, while carrying the drawback of neglecting the effect of FPZ size. Therefore, a new test method that can measure critical fracture energy (G_c) in mode-II fracture, is needed for evaluating critical properties of SFRM for simulating delamination.

At structural level, Braxtan and Pessiki (2011b) studied damage pattern in SFRM on a beam-column assembly subjected to quasi-static cyclic loading through large-scale experiments, where the cyclic

loading represented a strong seismic event. Substantial damage of SFRM in bottom flange of beam and partial damage of SFRM in web of beam were observed. Wang et al. (2013) conducted large scale experiments to investigate failure pattern of SFRM applied on cantilever steel columns subjected to large static and cyclic moments at the bottom of the column. The authors concluded that adhesion of SFRM to steel remains weak and noticeable peel-off of SFRM from steel surface occurs on the onset of large moments on the column.

Review of literature indicates that there is serious lack of understanding regarding the fracture performance of SFRM both at material and structural levels. Therefore, a new test method is developed for measuring stress-displacement relationship of SFRM over FPZ in both modes of fracture, namely mode-I and mode-II, by taking into account size of the FPZ.

3 Cohesive zone model concepts

In recent years, the concept of CZM is well-accepted to be an effective method for studying fracture mechanics problems through finite element models (Xu and Needleman, 1994; Alfano and Crisfield, 2001). In essence, CZM establishes a linkage among micromechanical fracture mechanisms and macroscopic structural deformation field by rendering fracture parameters into a material constitutive model. Fig. 2 depicts the application of CZM concept to SFRM-steel interface where traction-separation relationship is shown over the cohesive surface. Fracture process at interface starts with crack initiation, once the cohesive stress reaches cohesive strength ($\sigma_{\max}$) of SFRM. Crack initiation is followed by strain-softening along the localized cohesive zone. As such, interfacial opening displacement increases from zero to failure displacement (δ_f). This leads to complete delamination and appearance of new traction free crack faces.

There are numerous CZMs proposed in literature to cope with different material types and practical situations. The models developed by Hillerborg et al. (1976), Mi et al. (1998) and Alfano and Crisfield (2001) are a bilinear type. Xu and Needleman (1994) proposed an exponential form of traction-separation

relation. Trapezoidal cohesive law was proposed by Tvergaard and Hutchinson (1996) to deal with fracture in adhesive joints. Among other models, bilinear cohesive zone model has successfully been utilized by many researchers for modeling delamination of interfaces (Alfano and Crisfield, 2001; Camanho et al., 2003; Alfano et al., 2009; Atas et al., 2012; Ye and Chen, 2011; Lee et al., 2010). Bilinear model obviously assumes a linear softening rule; however, the other alternatives for softening part of the cohesive zone model are bilinear, exponential and higher polynomials. These types of softening laws, established for concrete, have been evaluated by Hofstetter and Meschke (2011). Alfano (2006) evaluated the influence of the shape of the interface law on the application of cohesive zone models and concluded that the degree of influence that shape of the cohesive law can impose depends on the ratio between the interface toughness and the stiffness of the bulk material. For a typical double-cantilever beam test, the solution was found to be practically independent from the shape of the cohesive law. While the difference among predictions of linear and exponential softening laws was negligible, the linear softening law always demonstrated the superior efficiency in terms of CPU time. Given the fact that it is intended to apply the developed cohesive laws in predicting the delamination of fire insulation from steel structures in practical scales, CPU time will be extremely crucial. Hence, a bilinear traction-separation law proposed by Alfano and Crisfield (2001), which can capture the accumulative delamination during unloading and subsequent reloading, is adopted in this study.

Fig. 3 shows CZM constitutive relations for SFRM in both normal (mode-I) and tangential (mode-II) directions. The model has a linear elastic portion followed by a linear softening part. Delamination is initiated when the contact stress at the SFRM-steel interface reaches cohesive strength ($\sigma_{\max}$ or $\tau_{\max}$) and subsequently progresses until the contact stress reaches zero value, the point at which delamination is completed. Once completely delaminated, further separation occurs without any contact stress. The delaminated surfaces may interact again, however, the contact behavior will be a standard one (i.e. frictional contact). If unloading takes place at any point on softening part, traction-separation follows a linear response and decreases to zero stress. Subsequent reloading does not follow the original stiffness,

instead takes the previous unloading path with reduced stiffness. This way, the effect of partial delamination and damage accumulation is taken into consideration. The analytical expression for mixed mode delamination (combination of constitutive relations depicted in Fig. 3) can be represented as:

$$\begin{Bmatrix} \sigma \\ \tau \end{Bmatrix} = \begin{Bmatrix} K_n \delta_n (1 - d) \\ K_t \delta_t (1 - d) \end{Bmatrix} \quad (1)$$

where, σ and τ are normal and shear cohesive stresses, K_n and K_t are normal and tangential contact stiffness, δ_n , δ_t are normal separation and tangential slip distance, and d is damage parameter which is expressed as:

$$d = \left(\frac{\Delta - 1}{\Delta} \right) \chi \quad 0 \leq d \leq 1 \quad (2)$$

$$\text{where, } \Delta = \sqrt{\left(\frac{\delta_n}{\delta_{n,o}} \right)^2 + \left(\frac{\delta_t}{\delta_{t,o}} \right)^2} \quad (3)$$

in which $\delta_{n,o}$ and $\delta_{t,o}$ are separation distances corresponding to normal and shear cohesive strength, respectively and the parameter χ is given as:

$$\chi = \frac{\delta_{n,c}}{\delta_{n,c} - \delta_{n,o}} = \frac{\delta_{t,c}}{\delta_{t,c} - \delta_{t,o}} \quad (4)$$

in which $\delta_{n,c}$ and $\delta_{t,c}$ are normal and tangential separation at the end of cracking, respectively.

For $\Delta \leq 1$ the damage parameter is zero ($d = 0$) and for $\Delta > 1$, d -value falls between zero and 1 ($0 < d \leq 1$). Note that, in 3D models isotropic behavior is assumed in terms of tangential slip distance:

$$\delta_t = \sqrt{\delta_{t,1}^2 + \delta_{t,2}^2} \quad (5)$$

where, $\delta_{t,1}$ and $\delta_{t,2}$ are tangential slip distance components. Fracture energies (G_n and G_t) at any displacement level are calculated as:

$$G_n = \int \sigma d\delta_n \quad (6)$$

$$G_t = \int \tau d\delta_t \quad (7)$$

The normal and tangential critical fracture energies (G_{nc} and G_{tc}) are computed as:

$$G_{nc} = \frac{1}{2} \sigma_{max} \delta_{n,c} \quad (8)$$

$$G_{tc} = \frac{1}{2} \tau_{max} \delta_{t,c} \quad (9)$$

For decoupled fracture modes, delamination occurs once the current energy level reaches a critical value, whereas for mixed mode delamination an interaction curve needs to be defined since both normal and tangential energies contribute to total fracture energy. In this study, a power law criterion established to predict delamination propagation under mixed mode loading is used which is prevalent in fracture mechanics (Alfano and Crisfield 2001):

$$\left(\frac{G_n}{G_{nc}} \right) + \left(\frac{G_t}{G_{tc}} \right) = 1 \quad (10)$$

where G_n and G_{nc} are normal current and critical fracture energy; and G_t and G_{tc} are tangential current and critical fracture energy.

4 Determination of cohesive zone properties of SFRM

As outlined in previous sections, to predict the crack propagation at SFRM and steel interface it is indispensable to establish the constitutive relations of SFRM in FPZ, namely cohesive laws. In this section, test procedures adopted to determine cohesive zone properties are presented.

4.1 Test procedures to evaluate cohesive zone properties

There are, in general, two approaches for obtaining stress-displacement relationship in FPZ of cementitious materials; direct approach and indirect approach. In direct approach, stress-displacement is measured by means of a tension test for Mode I fracture (Peterson, 1985; Reinhardt, 1987; Gu and Zhang,

1987). In this method, although pre-existing flaws start to grow at discrete locations during initial stages of loading, localization of deformation occurs in the FPZ once the maximum load has been attained (Cotterell and Mai, 1996). Specimen dimensions must be large enough to accommodate full development of the FPZ across the tensile area. Stress-displacement relationship obtained from a tension test can directly deliver all three CZM parameters namely, cohesive stiffness, cohesive strength and fracture energy. No further numerical work is therefore required for extracting CZM parameters. However, the fracture evolution across the tensile area must be uniform; otherwise local instabilities such as “bumps” are observed in stress-displacement curve (Hordijk et al., 1987).

There are various indirect methods proposed in the literature for deriving stress-displacement relationship in FPZ of cementitious materials. For instance, Li’s approach (1987) involves measurement of J -integral and crack tip opening displacement (CTOD) to obtain the stress-displacement curve. In this method, two specimens have to be used which makes interpretation of results difficult due to inhomogeneous behavior of cementitious materials. Indirect approach has also extensively been used for composite materials and interface of two materials (Sorensen and Jacobsen, 2003; Gordnian et al., 2008; Lee et al. 2010; Valoroso et al. 2013). In recent years, Double Cantilever Beam (DCB) specimens (ASTM D5528, 2013) and End Notched Flexure (ENF) (ASTM WK22949, 2009) specimens are widely utilized to extract the fracture energy in pure modes I and II, respectively. However, fracture energy is the only outcome from these tests. Two other parameters of cohesive laws, namely cohesive stiffness and cohesive strength, are therefore to be determined through numerical modeling. To extract these parameters, an ideal stress-displacement curve is assumed and numerical simulation is carried out. The predicted overall load-displacement relationship is compared to the experimental behavior and this iterative process is repeated until the best agreement is obtained between experimental and simulation results. However, due to mesh sensitivity of cohesive solutions, the above explained computational effort can be quite significant and the predicted cohesive zone properties may not be accurate. In fact, sensitivity analyses have shown that utilizing global load-displacement relationship for obtaining cohesive properties through an iterative

process, does not always lead to extracting both cohesive stress and cohesive energy (Alfano et al., 2011). To overcome above explained difficulties associated with identification of traction-separation laws using direct and indirect methods, a new procedure has been proposed by Blaysat et al. (2014) to identify cohesive zone behavior more rigorously. This new method is based on recent developments in the area of non-contact optical techniques and utilizes Integrated Digital Image Correlation (I-DIC) concepts.

With respect to fire insulation, DCB and ENF tests cannot be used because SFRM does not contribute to the structural capacity (strength) of SFRM-steel assembly. That is, delamination at SFRM-steel interface will not cause any softening in the overall load-displacement relationship. Single Cantilever Beam (SLB) specimens proposed by Tan et al. (2011) to measure fracture energy of SFRM in pure Mode I entails using a very thin steel substrate (0.35 mm) which may affect the interfacial fracture phenomenon. Tan et al.'s (2011) test is based on LEFM theory and therefore does not account for the strain-softening in FPZ. Further, no testing procedure has so far been proposed for measurement of fracture energy in pure Mode-II at SFRM-steel interface. Therefore, direct approach is adopted in this study to establish cohesive laws for mode-I and mode-II delamination at steel-SFRM interface.

4.2 Materials and specimen geometry

For evaluating fracture-based cohesive properties, three types of commercially available SFRM that are commonly used in building applications, have been selected. The generic type of these three SFRMs is summarized in Tab. 1. Fig. 4 illustrates the overall plate geometry and the specimens after saw cutting. All specimens were prepared at the manufacture's SFRM laboratory. After 6-weeks of curing, the specimens were carefully shipped to Michigan State University's Civil and Infrastructure Laboratory for fracture tests. Two sets of specimens, shown in Fig. 4, were tested for each SFRM type. The specimens were carefully cut to the desired dimensions. The clear space left between specimens is large enough to fit the clamps in between for constraining the specimen plate into the testing machine. Tensile test specimens measured 76.2 x 76.2 x 25.4 mm and shear test specimens measured 101.6 x 25.4 x 25.4 mm. With

respect to size of specimens, it was attempted to adopt as large specimens as possible to reduce the size effects and hence generate as realistic data as possible which can be applicable in practice. The issue of size effect has been studied by Bazant (1984), Bazant and Kazemi (1990) and Bazant and Kazemi (1991) for concrete and rock.

4.3 Experimental setup for mode-I delamination

A special test setup was designed for undertaking delamination tests on SFRM insulated steel plates to measure normal cohesive stress-displacement response. Details of the test specimens and the testing procedure designed for measuring mode-I delamination properties at steel-SFRM interface is depicted in Fig. 5a and Fig. 6a. A plywood block with thickness of 15 mm is carefully drilled at the center to which an eyebolt is screwed in. The wooden block is glued on top of tensile specimen using wood glue. After gluing wooden block to SFRM, wood surface is leveled and clamped to the steel plate to make a perfectly flat surface. After 24-hours, the specimens are unclamped and prepared for testing. The test is carried out on an electromechanical material testing system (MTS) shown in Fig. 6a. The steel plate is clamped to an I-beam, which is connected to bottom actuator, to prevent deformation of plate during the test. The eyebolt is connected to the upper rigid block using a shackle-eye nuts-threaded rod assembly. Special care is taken to ensure that no eccentricity exist between MTS loading direction and specimen center. Displacement-controlled load is applied on the specimens and load-displacement relationship is recorded while the loading rate is kept constant at $1\mu\text{m}/\text{sec}$. Test is terminated once the full fracture of SFRM occurs and specimen can no longer withstand any further load. For each SFRM type, 12 tests were conducted in mode-I delamination.

4.4 Experimental setup for mode-II delamination

Direct shear test is conducted to measure the stress-displacement response in mode-II delamination at the interface of SFRM and steel plate. The specimen details and testing method is illustrated in Fig. 5b and Fig. 6b. The SFRM block is pushed against the steel plate thereby inducing direct shear stresses at the

interface of steel and SFRM. The width of the test specimen along loading direction was chosen to be small enough to preclude cohesive failure within the SFRM. A small gap was introduced between the loading plate and test specimen plate so that friction between two plates is eliminated. The test is carried out through a displacement control loading technique with a constant displacement rate of $1\mu\text{m}/\text{sec}$. The stress-displacement recording is continued until the SFRM block is fully delaminated from steel surface and the total applied load returns to zero value. For each SFRM type, 12 tests were carried out in mode-II delamination.

4.5 Elastic modulus tests

The elastic modulus for three types of SFRM was determined by conducting compression tests on SFRM blocks of 50.8 mm x 50.8 mm x 50.8 mm size. Displacement controlled loading was applied with a constant displacement rate of $1\mu\text{m}/\text{sec}$. The measured elastic modulus on three types of SFRM is listed in Tab. 2.

5 Results from cohesive zone property tests

The force-displacement relationships recorded from tensile tests are shown in Fig. 7 for three types of SFRM insulated specimens. It is apparent that the response of Portland cement-based SFRM is relatively brittle as compared to the gypsum-based and mineral fiber-based SFRM. For gypsum-based and mineral fiber-based SFRM types, interfacial force rises almost linearly to critical cohesive strength, and subsequently, decreases with increasing normal displacement. The softening behavior observed in the force-displacement curves, confirms that the size of fully developed FPZ is noticeable for gypsum-based and mineral fiber-based SFRM. Even in the case of Portland cement-based SFRM, there is no rapid load drop as would be the case for elastic-brittle materials. For this SFRM type, force-displacement curve is nonlinear up to the peak load which is followed by a sharp drop to 20 percent of peak load as can be seen from force-displacement response in Fig. 7. Then the load response slowly diminishes to zero with further

interfacial deformation. Ultimate fracture displacement in this case is higher than those obtained for gypsum-based and mineral fiber-based SFRM.

In all specimens, prior to reaching to cohesive strength (peak load) there was no sign of crack development throughout the specimen. However, once damage is localized and FPZ formation starts, cracks started appearing in decay phase of force-displacement curve and get fully developed and visible upon reaching to the failure displacement. Delayed development of FPZ can be attributed to the fact that in plain tensile specimens no initial crack or notch is introduced. Consequently, this is no focus point for the formation of FPZ and thus dispersion of initial microcracking occurs. Since SFRM is substantially softer than steel ($E_{\text{SFRM}}=30 \text{ MPa} \ll E_{\text{steel}}=200 \text{ GPa}$) and also the applied loading on the specimen is very low (maximum 0.4 kN), deformation of steel accessories used in the tensile test has a negligible influence on the recorded displacement. In addition, the elastic contribution from FPZ can be neglected because FPZ is narrow compared with the thickness of specimen. However, the contribution of bulk SFRM to elastic deformation before reaching to cohesive strength should be accounted for. As will be shown shortly, the compliance of bulk SFRM affects the initial elastic response and thus the associated energy and displacement are removed from stress-displacement curves while establishing cohesive laws.

From cohesive strength viewpoint, Portland cement-based SFRM possesses the highest strength, while gypsum-based SFRM possesses moderate strength and mineral fiber-based SFRM exhibits the least cohesive strength as can be seen in Fig. 7. Cohesive stiffness also decreases from Portland cement-based SFRM to gypsum-based SFRM, and from gypsum-based SFRM to mineral fiber-based SFRM, as was the case for cohesive strength. Further, as is apparent from the area under each curve, Portland cement-based SFRM offers the highest level of fracture energy, while gypsum-based SFRM and mineral fiber-based SFRM exhibit moderate and low level of fracture energy, respectively. It should be noted that, there is substantial difference in fracture energy between Portland cement-based and gypsum-based SFRM, whereas this is not the case with gypsum-based and mineral fiber-based SFRM. Further, it can be seen in Fig. 7 that there is a nonlinear behavior in the case of Portland cement-based SFRM before reaching to

cohesive strength. In this case, a different microcracking mechanism both at steel-SFRM interface and bulk SFRM can be responsible for the observed nonlinearity.

In Mode-II fracture, as is depicted in Fig. 8, all three materials show similar force-displacement trend though with different level of cohesive zone parameters. Shear force at steel-SFRM interface surges to the maximum cohesive strength and subsequently reduces smoothly as the microcracking activity is completed in FPZ and failure crack tip displacement is attained. Hence, in shear mode of delamination, ductile behavior is dominant in all three types of SFRM, which once more endorses the fact that the size of FPZ is considerable for SFRM. Portland cement-based SFRM provides the superior performance both in terms of cohesive strength and fracture energy. Gypsum-based SFRM performs better than mineral fiber-based SFRM; however, the level of enhancement from mineral fiber-based SFRM to gypsum-based SFRM is not comparable to the one from gypsum-based SFRM to Portland cement-based SFRM. Further, interfacial stiffness is proportional to the level of cohesive strength as was the case with mode-I fracture. Overall, force and displacement peak values shown in Fig. 7 and Fig. 8 suggests that cohesive resistance in mode-II is higher than mode-I. Note that, crack progression phenomenon in shear tests was similar to the one observed in tensile tests, as discussed above.

Displacement ductility over the cohesive zone is an additional parameter of interest for characterizing cohesive zone behavior. This parameter determines the extent of the strain-softening portion of cohesive stress-displacement curve (as illustrated in Fig. 3). Displacement ductility over the cohesive zone (μ_n and μ_t) is defined here as the ratio of fracture displacement to displacement corresponding to cohesive strength, as shown in Fig. 3. It is clear from Fig. 7 and Fig. 8 that mineral fiber-based SFRM possesses the highest displacement ductility over cohesive zone, while gypsum-based SFRM possesses moderate ductility, and Portland cement-based SFRM offers the least ductility. It can be inferred that, the softer the SFRM is, the higher the displacement ductility over the cohesive zone will be.

It was indicated in previous section that results of direct test method are acceptable provided the failure surface progresses uniformly through tensile or shear zones. Fig. 9 illustrates the uniform evolution of damage at steel-SFRM interface in tensile and shear tests. In tensile tests, one of the specimens, out of 12 tested specimens from Portland cement-based SFRM, did not show this behavior and the result from this specimen was discarded. In shear tests, all 12 specimens developed a uniform shear failure at the steel-SFRM interface. Also, it was discussed that force-displacement curves for mode-I fracture show ductile behavior in all cases except in the case of Portland cement-based SFRM under tensile loading. Even in this case, it was concluded that the material does not behave purely brittle. In addition, all three types of SFRM demonstrated ductile performance in Mode-II fracture. Therefore, from fracture mechanics perspective, SFRM may be considered as a “quasi-brittle” material, rather than “brittle” material.

Average cohesive strength obtained from tensile and shear tests are plotted in Fig. 10. The cohesive stresses are calculated by dividing the recorded force to cross sectional area under tension and shear ($\sigma=P/A$). As is represented by error bars, the scatter in the data is relatively small which proves the reliability of results. The mean values of cohesive strength are tabulated in Table. 2. The shear cohesive strength is almost twice as high as normal cohesive strength for all three types of SFRM. In both normal and shear modes of fracture, Portland cement-based SFRM exhibits the highest cohesive strength, gypsum-based SFRM exhibits average strength and mineral fiber-based SFRM exhibits the least strength. Manufacturer of these SFRMs has only provided the normal cohesive strength (bonding strength) which is included in Table. 2. The normal bonding test (adhesion test) is performed by manufactures according to ASTM E736 (2006). In this method, a metal of plastic disk containing a hook is attached to the surface of SFRM using a quick-setting adhesive. Then, a spring-type weighing scale is attached to the hook and the scale is pulled. The bond is considered acceptable provided the SFRM can endure the applied minimum load. The normal cohesive strength from tests for gypsum-based and mineral fiber-based SFRM are very close to value given by the manufacturer; however, for Portland cement-based SFRM,

manufacture reports a very high upper bond value for normal cohesive strength which was not observed in the tests carried out in this study.

Fig. 11 shows the critical fracture energy measured in mode-I and mode-II fracture tests. The error bars in this case are also fairly small validating reproducibility of fracture energies extracted from the experiments carried out in this study. The order of performance in terms of fracture energy is identical to the one mentioned above for cohesive strength. However, the ratio of shear fracture energy to normal fracture energy is 4 and 5 for gypsum-based and mineral fiber-based SFRM, respectively, while this ratio is close to 2 for Portland cement-based SFRM. Further, irrespective of all differences among the quantities and performances of SFRMs, one fact is very obvious that the amount of critical fracture energy is low. This characteristic of SFRM raises the concern regarding the delamination at SFRM-steel interface when the steel substrate undergoes large strains under the action of extreme loading events on steel structures.

To accommodate the experimentally obtained stress-displacement curves with bilinear CZM described in section 3, the concept of equal energy can be adopted as displayed in Fig. 12. The displacement corresponding to cohesive strength can be extracted by equalizing the area under the curve up to experimental culmination displacement with the corresponding area of a triangle in bilinear model. The elastic energy absorbed by bulk SFRM is removed from the total elastic energy. The elastic deformation of bulk SFRM is calculated using Hook's law by knowing the elastic modulus and maximum stress experienced by SFRM during test. The displacement corresponding to cohesive strength is also reduced by elastic deformation of bulk SFRM. Likewise, the failure displacement at cohesive zone can be obtained by associating the total areas under experimental curve (reduced due to compliance of bulk SFRM) and bilinear model. The result of this equalization process is plotted in Fig. 13 and Fig. 14 where CZMs pertaining to mode-I and mode-II fracture for three types of SFRM are shown, respectively. Table 2 presents the cohesive zone parameters along with elastic modulus for three type of SFRM. These CZMs

can be utilized for simulation of progressive delamination at steel-SFRM interface in different structural assemblies insulated with SFRM.

Lastly, the size of the cohesive zone (or in other words, FPZ) is to be predicted prior to identifying the element size in numerical modeling such that enough number of elements span the cohesive zone to ensure as correct dissipation of energy as possible. Turton et al. (2007) have summarized some of the expressions with respect to computation of cohesive zone length. In this study the cohesive zone length is computed using the following expression, given by Hillerborg et al. (1976), for concrete as a cementitious material:

$$l_{cz} = \frac{EG_c}{(\sigma_{coh})^2} \quad (11)$$

in which, E , G_c and σ_{coh} are elastic modulus, fracture energy release rate and cohesive strength for fracture mode-I, respectively. The cohesive zone length computed by Eq. (11) for gypsum-based, Portland cement-based and mineral fiber-based SFRM types are 187 mm, 481 mm and 79 mm, respectively. By carefully inspecting Eq. (11), and given the corresponding quantities for SFRM, it is clear that the large size of cohesive zone can be attributed to very low level of cohesive strength (with square power in denominator). The large size of cohesive zone indicates that LEFM is not applicable for evaluating fracture in SFRM. It should be noted that, length of fully developed fracture process zone is size and geometry-dependent. In fact, in small specimens, FPZ cannot fully develop. This issue has been dealt with by Bazant and Kazemi (1990) for concrete and rock. However, there is no research on size of FPZ developed at steel-SFRM interface. The equation (11), which is also termed characteristic length in fracture mechanics literature (Cotterell and Mai, 1996), can only provide an approximate extension of fully developed FPZ at steel-SFRM interface. This equation is utilized in this study to only approximate the size of FPZ (cohesive zone) in order to have an estimation of initial mesh size over the cohesive zone. Nonetheless, mesh sensitivity analyses is performed to ensure that sufficient number of cohesive elements (at least 10 elements) is embedded in cohesive zone to correctly capture the nonlinearity in this zone.

6 Numerical simulations

To demonstrate the usefulness of cohesive zone properties of SFRM in predicting delamination of SFRM from steel structures, two sets of numerical studies is carried out. In the first set of numerical modeling, delamination in two separate modes of fracture are simulated, while in the second set, mixed-mode delamination is modeled. A finite element model developed in ANSYS software (Kodur and Arablouei, 2013) is used to simulate delamination phenomenon by implementing the cohesive laws developed in the above discussed experimental program.

6.1 Numerical modeling of fracture tests

In the first set of simulations, the fracture tests carried out in this study on three types of SFRM are simulated through finite element model. Steel substrate and SFRM are discretized using 8-noded solid elements available in ANSYS. At the interface, surface-to-surface contact is employed such that steel and SFRM surfaces are discretized using 4-noded target and contact elements, respectively. The proposed cohesive laws developed using experimental data are utilized here as steel-SFRM interface constitutive model. As previously indicated, CZM requires to be coupled to interface elements in order to model progression of delamination. In this study, contact elements are adopted for this purpose. Initially, two surfaces are assumed to be bonded and subsequently, under increasing loading conditions, separation or slip distance is simulated in accordance with corresponding CZM. The test conditions are represented in the numerical model with as much details and accuracy as possible in terms of boundary conditions and geometrical aspects. Boundary conditions and loading methods encountered in experiments, which were illustrated in Fig. 5 and Fig. 6, are adopted in the numerical modeling. Fig. 15 depicts the finite element model generated to predict both modes of fracture observed in the experiments. The model comprises of the steel plate, SFRM, wooden block and eyebolt. The finite element size over the cohesive zone was kept small enough (2 mm) to eliminate approximation problems. Give the value of characteristic length computed by equation (11), this is a very fine mesh. The minimum number of elements spanning over the

cohesive zone has not been well-established (Turton et al., 2007). The values between 2 to 10 have been used by researchers (Falk et al., 2001; Dávila et al., 2001; Moës and Belytschko, 2002). In this study, results of analysis for mesh size of 2mm and 5mm were identical. SFRM cohesive zone properties derived in the experiments are utilized (Table 2). The cohesive laws depicted in Fig. 13 and 14 are used to trace the interface behavior. The elastic modulus of SFRM, obtained through compression tests was utilized. The steel truss member is assumed to be of A992 ($\sigma_y=355$ MPa, $E=200$ GPa and $\nu=0.3$).

6.2 Numerical modeling of plate-SFRM assembly under tension

In the second set of simulations, a delamination test reported by Braxtan and Pessiki (2011a) on an insulated steel plate is modeled. Fig. 16a and Fig. 16b depict the test plate setup and geometry, respectively. The test plate measured 1100 mm long $\times$ 152 mm wide $\times$ 6 mm thick and was covered with mineral fiber-based SFRM at the central 457 mm of one face of plates. A distance of 305 mm was then left bare on each end enabling specimen to fit in universal testing machine's upper and lower jaws. Strain gages were attached to steel plate to measure the strain level during tensile tests. The plate was loaded through displacement control at a loading rate of 1.27 mm/min.

The finite element model of plate-SFRM assembly is illustrated in Fig. 16c. The steel plate is discretized using 4-noded shell elements (SHELL181) that have three translational and three rotational degrees of freedom at each node. SFRM is discretized using 8-noded solid elements. SFRM-interface behavior is simulated through contact interaction elements by implementing the CZM as material constitutive model. Mesh sensitivity analysis was carried out to find the optimum mesh size. While incrementally reducing the mesh size from 20mm to 10mm, it was found that, there is negligible improvement from mesh size of 12 mm to 10 mm. The average cohesive properties of mineral fiber-based SFRM derived in this study were used to model bulk SFRM and SFRM-steel interface behavior. The grade of steel used in this plate is A36 ($\sigma_y=325$ MPa, $E=200$ GPa and $\nu=0.3$).

6.3 Nonlinear solution techniques

Numerical solution in the case of contact interaction analysis is highly nonlinear making computational efforts cumbersome, even though material properties remain elastic. The contact algorithm used in this study is a “pure penalty” algorithm (ANSYS, 2013) that uses a contact spring to establish a relationship between the two contact surfaces. In contact solutions, convergence problems arise when the response reaches softening zone of CZM. Crisfield et al. (1994) inferred that Newton-Raphson method is not efficient enough due to convergence issues while using either load-controlled (with Arc Length) or displacement-controlled loading. To rectify the problem, Crisfield et al. (1994) proposed line search procedure. In this study, displacement-controlled loading, in conjunction with line search method, is used thereby enhancing the capabilities of Newton-Raphson method to achieve convergence. Nonetheless, convergence issues arise at some load steps which is treated by adopting nonlinear stabilization method provided in ANSYS. Nonlinear stabilization in ANSYS can be understood as adding an artificial damper or dashpot element at each node of an element. The damper element coefficient is then optimized such that the stabilization process will not influence the accuracy of solution.

7 Results of numerical simulations

Results from numerical modeling of fracture tests conducted in this study on three SFRM types and plate-SFRM assembly under tension is presented here. In the first set of simulations, the numerical simulations examine the numerical technique at each separate fracture modes. The numerical and experimental results are superimposed in Fig. 17 showing acceptable correlation among two sets of results for three types of SFRM. Both cohesive strength and fracture energy are satisfactorily predicted in this case. For mode-II fracture, the stress-displacement curves are shown in Fig. 18. A quite reasonable agreement can also be seen in Fig. 18 between numerically predicted stress-displacement relationship and the observed experimental behavior. As it can be seen, in both cases, predicted stress-displacement relationship has a bi-linear shape, which is expected due to the fact that the input CZM is bilinear. Above explained two examples of simulation demonstrate that the developed numerical procedure is practically capable of predicting observed fracture mechanisms for both modes of fracture.

In the second set of results, predicted delamination progression on steel plate covered with mineral fiber-based SFRM is shown in Fig. 19 and compared to the one obtained from experiment. The delamination length at the end of steel plate is predicted to be 134 mm at strain level of $11.8\epsilon_y$, while the measured fracture extent is 127 mm in experiments at strain level of $10.4\epsilon_y$. Given the fact that average values of fracture properties were used for SFRM in numerical model, which may not be exactly identical to the SFRM properties in the experiment, the correlation between predicted and measured extent of fracture is fairly satisfactory. This clearly shows the applicability of cohesive zone models proposed in this study for modeling progressive delamination of SFRM from steel structure where mixed-mode delamination governs failure.

8 Summary and conclusions remarks

In this paper, cohesive zone response properties of fire insulation in mode-I and mode-II fracture was evaluated through a set of direct tensile and shear strength tests on three types of SFRM commonly used in practice. Based on the results outlined in this paper following points are highlighted:

- Strain-softening behavior of spray-applied fire-resistive material (SFRM) at steel-SFRM interface clearly infers that SFRM is not a purely brittle material; instead, it is a quasi-brittle material.
- Presence of considerable size of fracture process zone in SFRM infers that application of linear elastic fracture mechanics is not suited for characterizing fracture in quasi-brittle type of SFRM and more advanced approaches such as Cohesive Zone Model is to be applied to evaluate realistic response.
- Medium density Portland cement-based SFRM possesses the highest cohesive strength and fracture energy while having the least displacement ductility over the cohesive zone.
- Medium density gypsum-based SFRM possesses lower cohesive strength and fracture energy, as compared to Portland-cement based SFRM, and has higher displacement ductility over the cohesive zone.

- Mineral fiber-based SFRM possesses the least cohesive strength and fracture energy but has the highest cohesive ductility.
- Good correlation between predicted and measured fracture response parameters for three types of SFRM and steel plate-SFRM assembly under tension, indicates that the proposed cohesive zone properties, developed through experiments in this study, can be utilized in further sensitivity studies with respect to cohesive zone parameters namely cohesive strength, fracture energy and cohesive ductility. In addition, the proposed cohesive laws can be used for quantifying progressive delamination of SFRM from steel structures subjected to complex loading scenarios.

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Tab. 1 Three type of SFRM utilized in experiments

Name	Type of SFRM
A	Medium density gypsum-based
B	Medium density Portland cement-based
C	Mineral-fiber-based

Tab. 2 Cohesive zone model parameters obtained in experiment for three types of SFRM

SFRM type	$\sigma_{\max}$ (kPa)	$\tau_{\max}$ (kPa)	$\tau_{\max}/\sigma_{\max}$	G_{cn} (J/m ²)	G_{ct} (J/m ²)	G_{ct}/G_{cn}	K_n (kPa/mm)	K_t (kPa/mm)	μ_n	μ_t	E (MPa)	Manufacture $\sigma_{\max}$ range (kPa)
A	22.9	49.6	2.2	7.9	32.8	4.2	57.3	107.9	1.73	2.98	11.5	7.2-20.5
B	52.8	107.3	2.0	33.7	74.4	2.2	57.4	162.6	1.40	2.11	38.4	20.8-409.6
C	13	24.6	1.9	4.3	22.5	5.2	39.3	61.4	2.03	4.63	2.6	7.2-17.9

Figure 1

Fig. 1 Strain-softening at fracture process zone for SFRM

Figure 2

a) Typical beam with SFRM insulation subjected to gravity loading

b) Progression of cracks leading to delamination of SFRM at bottom flange of beam

Fig. 2 Cohesive zone model concepts at interface of steel structural member and SFRM

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Fig. 17 Comparison of force-displacement relationship predicted from numerical model with measured values from experiments for mode-I delamination

Figure 18

Fig. 18 Comparison of force-displacement relationship predicted from numerical model with measured values from experiments for mode-II delamination

Fig. 19 Delamination length predicted and measured on a plate covered with mineral fiber-based SFRM

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