NUMERICAL STUDY OF THE THERMAL BEHAVIOUR OF STEEL MEMBERS WITH DAMAGED SFRM COATINGS

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1. ABSTRACT

This study addresses numerically the problem of the structural damage of cementitious Sprayed Fire Resistive Materials (SFRM) that are applied on steel members for fire protection, and the effect the damaged coating has on the fire resistance of the steel member. In order to understand the failure mechanisms of the SFRM coating, initially the flexural test of a steel plate with SFRM coating is modelled numerically, and the failure patterns of the simulation are compared successfully with the experimental results. Then, a more complex model of an IPE beam with SFRM coating, under 3-point flexural load is simulated and the damage of the coating and the interface bond is studied. Subsequently, a parametric thermal analysis is conducted on the beam under ISO-834 thermal load, examining the effect the crack width has on the fire resistance of the beam.

2. INTRODUCTION

Structural steel is a material widely used in engineering applications due to its high structural strength and resistance. These qualities, however, deteriorate rapidly at higher temperatures, necessitating the protection of steel against thermal loads. Thermal loads can be a result of an accidental event, such as a fire or they can be caused by special operating conditions of the structure.
A widely used method of passive thermal protection of structural steel is the application of fire protective materials at the surface of the structural members. For common fire protection requirements, up to two hours, intumescent paints are preferred, due to their simple application and esthetically pleasing result. In larger scale projects and when fire resistance requirements exceed two hours, the use of intumescent paints is no longer cost effective. In such cases the materials of choice are the cementitious Sprayed Fire Resistive Materials (SFRM), which are mixtures based on cement, gypsum, vermiculite and perlite,

that are sprayed directly on the steel structural members. These materials, apart from their lower cost, are relatively low weight and have low thermal conductivity which makes them suitable for fire protection. Their main disadvantage, however is their low mechanical (structural) resistance. Cementitious SFRMs exhibit brittle failure and weak adhesive strength, and they can be easily damaged when they are subjected to small deformations, even within the elastic range of steel. Small deformations can be imposed on a structure due to a minor earthquake, or due to wind loads, and although the steel members will not sustain any damage, the fire protective coating may exhibit a certain level of damage. This damage, many times cannot be observed, because the structural members are not visible due to the architectural design. Therefore, it is necessary to be able to calculate, or estimate the damage of the protective coatings through the observation of other parameters, like the applied loads or relative deformations in other visible parts. The key issue of such an approach is the analysis and understanding of the damage mechanisms of SFRM coatings and its correlation with the loading conditions.

In this study, a numerical simulation of the damage mechanisms of cementitious SFRM in normal temperature is performed initially on two structural members, firstly on a simpler model of a steel plate and then on an I beam. Subsequently, a thermal analysis is conducted on the beam under ISO-834 thermal load, with various degrees of damage on its fire protective coating, in order to examine the difference in its fire resistance.

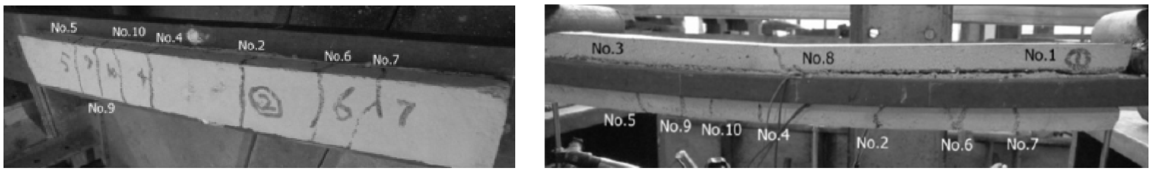
3. FAILURE MODES OF CEMENTITIOUS SFRM COATINGS

3.1 Tests on SFRM coated plates under tensile, compressive and flexural loading

Thick cementitious fire coatings have both low tensile strength (0.05 MPa) and low compressive strength (0.59 MPa) and express brittle failure [1]. At the interface between the structural steel and the coating the normal bonding strength is 0.04 MPa and the shear bonding strength is also very low, at 0.07 MPa.

The results of tensile, compressive and flexural tests on steel plates with SFRM coatings on both sides [2] showed that in the axial tensile loading of the plate, as the load increased causing steel strains of 0.08%-0.12%, interfacial cracks formed at both ends of the SFRM coating which propagated towards the middle of the plate, followed by transverse cracks that kept getting larger until the end of the test. In axial compressive loading tests, interfacial cracks initiated at both ends when the steel strain become approximately 0.2%, which propagated towards the middle of the specimen. At a steel strain of 0.3% the coating peeled off without internal damage. Under flexural loading, the former damage mechanisms were observed on the tension side and the compression side of the plate, respectively. On the tension side, the coating started displaying cracks on the interface of the two materials at both ends and then, with transverse cracks, it was fractured into several segments that remained attached on the steel plate until the end of the test (*Fig. 1a,b)*. On the compression side, the coating initially debonded from steel from both ends until near the middle, where it remained attached to the plate and later with a transverse crack separated from the plate.

The results of the tests indicated that there are two basic mechanisms that define the failure of SFRM coatings applied on steel members: a) debonding between the SFRM and steel, which develops at the interface of the materials and b) mechanical failure of the SFRM (cracking or crushing).



a) b)

Fig. 1. a) Cracking on tension side; b) SFRM damage at the end of the test [2]

3.2 Numerical simulation of the mechanical failure of SFRM on steel plate

Initially, in order to validate the numerical simulation of the failure mechanisms of SFRM coatings, the above mentioned flexural tests on the plates where simulated with the FEM, using the non-linear analysis software MSC MARC [3]. The numerical study considered a steel plate coated with SFRM on both sides, under four point flexural loading (*Fig. 2*). The mechanical properties of the materials at normal temperature are given in *Table 1.*

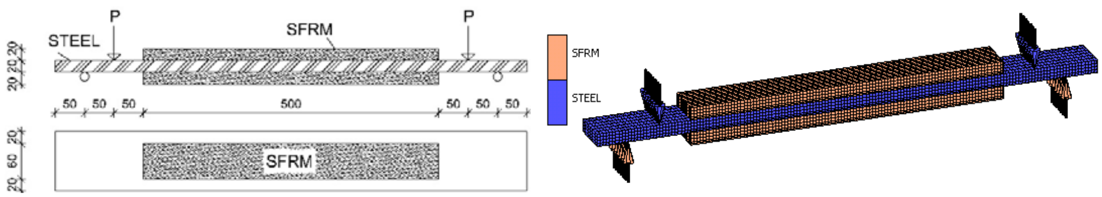


Fig. 2: a) Test configuration (dimensions in mm) and b) mechanical model of the SFRM coated steel plate

The steel plate is modelled using eight-node, isoparametric, arbitrary hexahedral solid elements and the cementitious coating is modelled by 20-node solid elements. The material behavior is simulated using a smeared cracking model that is typically applied to brittle materials as e.g. concrete. In tension, when the critical stress is reached, a crack develops in the material, which is perpendicular to the direction of the maximum principal stress. Then the stress in the direction of maximum stress, follows a descending softening branch until there is no stress. In compression, the stress-strain curve is linear until the critical compression stress is reached, followed by a fully plastic branch. The interface interaction between the normal and tangential interfacial stresses is modelled using the Yamada-Sun stress criterion [4] which has the form:

$$A = \left(\frac{\sigma_n}{S_n}\right)^2 + \left(\frac{\sigma_t}{S_t}\right)^2 < 1 \quad (1)$$

where, σ_n is the normal interfacial stress, σ_t is the tangential interfacial stress, S_n is the normal bonding strength and S_t is the shear bonding strength.

Initially, the two faces of the contact bodies are “glued” together with constraints to all displacement components between the corresponding nodes. During the analysis, the normal and tangential stresses are calculated for every node pair and when $A = 1$ the “glued” connection is released, permitting the development of relative displacements between the two bodies, while the normal and tangential stresses are redistributed.

On the compression side, delamination starts occurring at both ends of the coating. In the sequel, the interfacial cracking propagates towards the center of the coating and when the curvature of the plate is 0.098 m^{-1}, only a very small area of the coating remains attached to the steel plate. This is shown in *Fig. 3a*, where the area of the SFRM still attached to the plate is indicated with blue color and the area that has debonded is presented with yellow.

As the curvature increases, the bonded surface decreases, until the coating is almost completely detached from the plate. On this side, cracking occurs near the middle of the coating, (*Fig. 3b)*. As the curvature increases, the cracks get deeper, but don't extend to the outer surface of the coating.

Steel	E	v	E_p	f_y	
	200 GPa	0.2	1000 MPa	315 MPa	
Cementitious coating	E	v	E_s	f_t	f_c
	40.33 MPa	0.3	20 MPa	0.05 MPa	0.59 MPa
Interface	S_n			S_t	
	0.04 MPa			0.07 MPa	

E=Elastic modulus, v=Poisson's ratio, E_p=Hardening slope, f_y=Yield stress, E_s=Softening slope, f_t=Ultimate tensile stress, f_c=Ultimate compressive stress, S_n=Normal bonding strength, S_t=Shear bonding strength

Table 1. Material mechanical properties at normal temperature

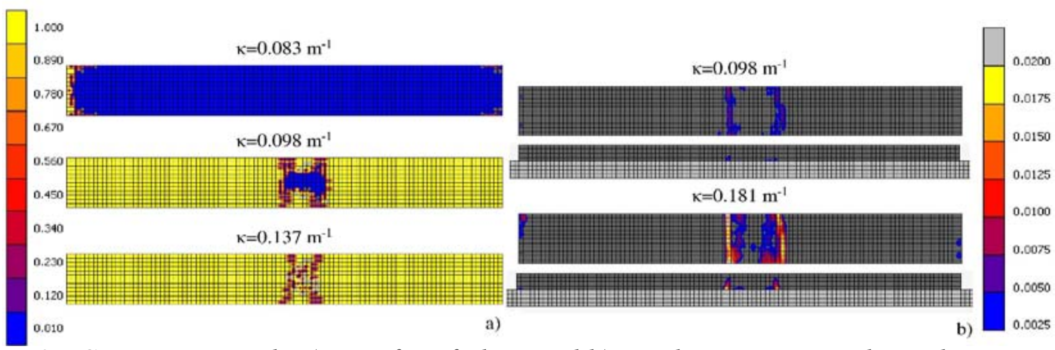


Fig. 3: Compression side a) Interface failure and b) cracking pattern and eq. plastic strain (plan and side views-SFRM in tension is not shown)

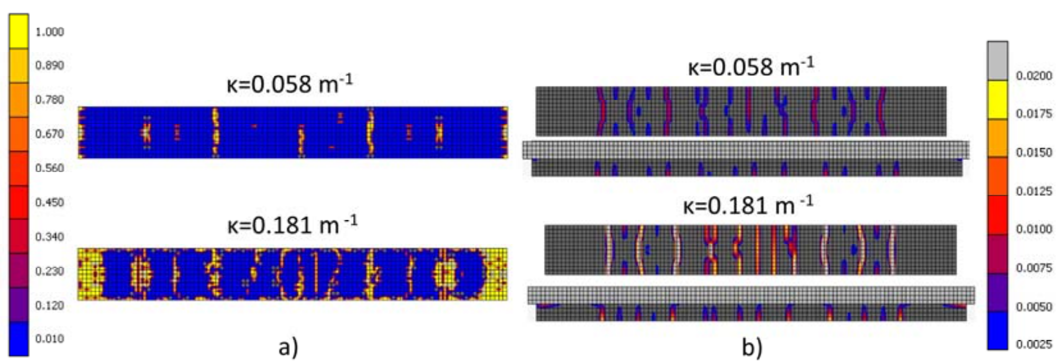


Fig. 4: Tension side a) Interface failure and b) cracking pattern and eq. plastic strain (plan and side views-SFRM in compression is not shown)

On the tension side the phenomenon is more complex because the progress of the delamination is affected by the creation of transverse cracks. Initially, the delamination begins at both ends, at a curvature of 0,051 m^{-1}. At that point, transverse cracking begins on the surface of the tension side of the cementitious coating. As the curvature increases, the cracks increase in depth and width. After the formation of cracks, the delamination (that has already begun at the ends of the coating) propagates towards the center, until it reaches the nearest transverse crack, where it stops. The development of the transverse cracks hinders the further spread of the delamination, preventing the total detachment of the coating from the steel plate (*Fig. 4a,b)*. The final failure mode of the applied coating on both sides of the steel plate, is fully captured by the model. The coating on the tension side of the plate is divided into several segments that are still attached to the steel plate. On the compression side, the fireproof coating debonds from the steel plate with minimal transverse cracking.

3.3 Numerical simulation of the mechanical failure of SFRM coating on IPE beam

After validating the simulation of the mechanical failure mechanisms of SFRM coatings in the simpler models of the steel plates, the method is applied on an IPE200 beam with 2 cm SFRM coating along the perimeter. The beam has a length of 1.40m and is subjected to 3-point bending. The mechanical properties of the materials and the interface are taken as in the previous paragraphs.
Initially, before any damage occurs at the cementitious coating, the interface between the two materials fails, due to normal stress along the flanges and tangential shear stress along the web. The interface bond begins to fail at the flanges, at the midspan of the beam and also at the supports due to localized loads. As the load increases, further delamination occurs at the flanges and propagates also at the middle of the web, which later progresses along the full length of the beam. The evolution of the interface failure is shown in *Fig. 5* with yellow color. The loading state is described by the fraction of the maximum vertical displacement of the beam (v) against its length (L).

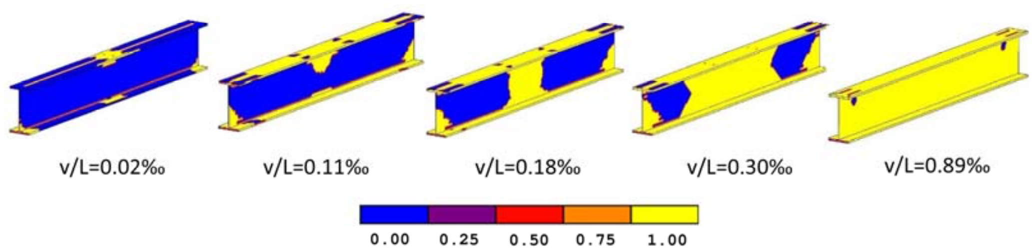


Fig. 5: Evolution of interface failure

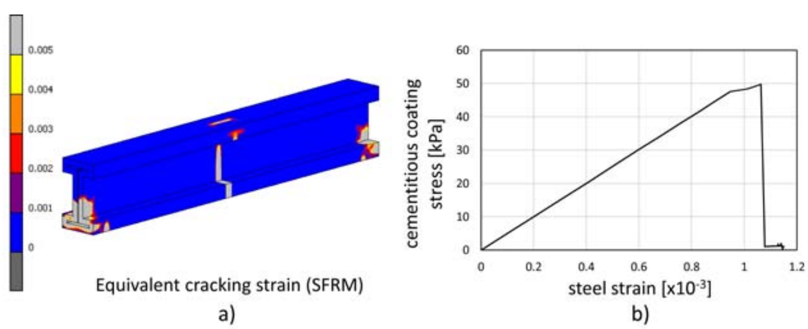


Fig. 6: a) Equivalent cracking strain at the SFRM coating, b) SFRM stress vs steel strain at the middle of bottom flange

Mechanical failure of the SFRM coating occurs much later, in the form of a transverse crack in the middle of the beam, initiating at the bottom of the lower flange, extending upwards along the coating of the web and reaching the top flange *(Fig. 6,a)*. The crack appears when v/L = 2.32‰, long after the extensive failure of the interface bond which occurs at v/L = 0.89‰. Steel strain at the occurrence of the crack is 1.07‰ *(Fig 6,b)*, a value that is in quite good agreement with the axial test results which showed that the SFRM coating failed at steel strains of 1.2 ‰. The damage that occurs at the SFRM coating near the beam supports due to the localized character of the loads is not taken into account during this study.

4. THERMAL ANALYSIS OF THE IPE200 BEAM

In this paragraph, the impact that the damage of the SFRM coatings has on the fire resistance of the steel structural members is evaluated. In the case of the steel beam subjected to 3-point bending, the main form of damage is the development of a transverse crack along the coating at mid-span. The crack width may initially be very small, but, as the load increases, the crack may become larger, exposing further the steel section to the thermal loads. A parametric study is conducted, regarding the crack width, and its effect on the temperature field of the steel beam when it is exposed to 1-hour ISO-834 thermal loading along the outer perimeter. The cracks considered in the parametric study have widths of 0.25cm, 0.50 cm and 1.00 cm. For reference, a fully protected and an unprotected steel section are also simulated.
For the thermal analysis, only a part of the beam is modelled, which extends 0.20m on either side of the middle of the beam (*Fig. 7,b)*. The insulated steel beam is subjected to external thermal loading and the heat is transferred to the steel beam and the SFRM coating through radiation and convection. At the interface, the two materials are considered to have the same temperature. The radiation heat transfer is implemented in the model through a radiating surface (emissivity = 1) placed opposite the coating, along the outer perimeter of the section, which undergoes a temperature rise according to the ISO-834 curve. The heated surface radiates to the coated, or the uncoated steel (crack), taking into account the corresponding view factors. Natural convection is modelled by a surface film applied on the corresponding exposed SFRM coating or steel opposite the radiating areas, using a heat transfer coefficient for air of 25 $W/m^2 \cdot °K$.
The guidelines of EC3, Part 1-2 [5] were adopted for the thermal properties of steel in elevated temperatures. Regarding the cementitious SFRM coating, the thermal properties are given in *Table 2*.

Temperature [°C]										
25	50	100	200	300	400	500	600	800	1000	1200
Specific Heat Capacity [J/(kg·K)]										
801.6	868.4	708.4	925.4	1084.7	1147.5	1255.3	1299.1	1369.6	1411.3	1461.3

Emissivity	**Density [kg/m³]**	**Thermal Conductivity [W/(m·K)]**
0.85	313.7	0.2

Table 2. Thermal properties of the cementitious SFRM coating

The evolution of the maximum temperature of the steel beam for the simulated models is given in *Fig 7,a*. Along with the temperature time histories, the ISO-834 time-temperature curve and the failure criterion of single point maximum temperature (20+649=669°C) for unrestrained steel beams according to ASTM-119 [6] are given. A representative temperature distribution in the steel beam is given in *Fig. 7,c*.
The results of the maximum temperature evolution in the steel beam, indicate that even a small crack, of 0.25cm, can affect the temperature development in an SFRM insulated steel section. In the specific case of the IPE200 beam, the 0.25cm crack on the coating reduces the fire resistance of the beam by 7 minutes, according to the ASTM-119, single point criterion, and a crack of 1cm, reduces the fire resistance by 19 minutes, which is about 1/3 less compared to the undamaged SFRM coated section. It is also evident, however, that an

unprotected beam will fail after only 13 minutes of ISO-834 thermal exposure, underlining the significance of fire the insulation of steel structural members.

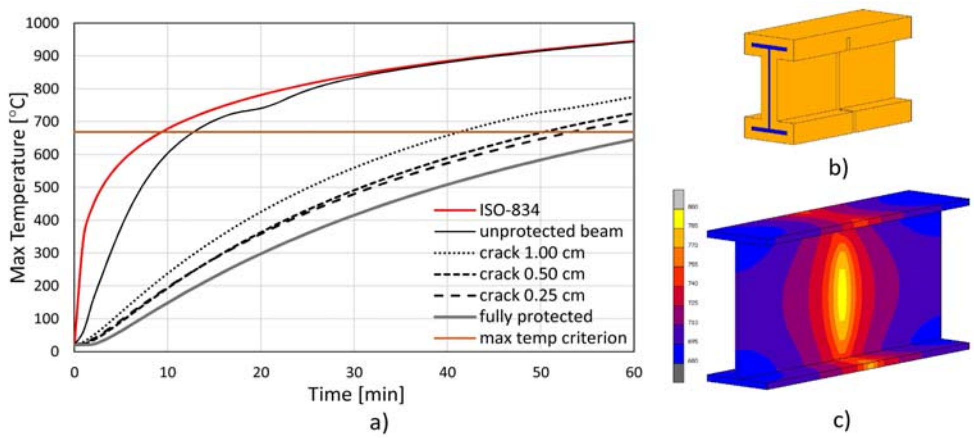


Fig. 7: a) Maximum temperature evolution of steel for the parametric models, b) FEM model with crack c) Temperature distribution in the steel beam

5. CONCLUSIONS

The failure mechanisms of cementitious SFRM coatings applied on steel members were successfully simulated, reproducing accurately the damage patterns of coated steel plates, which consist of a) the failure of the bonding interface between the materials and b) the mechanical failure of the SFRM coating due to cracking. The simulation method was applied on an IPE200 SFRM coated beam, and the damage of the coating was determined, which consisted of a transverse crack along the middle of the beam. After the corresponding thermal analysis, it was shown that even one crack in the coating could reduce the fire resistance of the beam by 19 min, 32% of the total fire resistance time of the undamaged coating. Structural failure of a member 32% earlier than expected, could be fatal for the occupants or the rescue teams operating on the scene, thus the integrity of the fire protection coatings and their damage is a problem that should also be considered during the fire design or maintenance of steel structures.

6. REFERENCES

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ΑΡΙΘΜΗΤΙΚΗ ΜΕΛΕΤΗ ΤΗΣ ΘΕΡΜΙΚΗΣ ΣΥΜΠΕΡΙΦΟΡΑΣ ΜΕΤΑΛΛΙΚΩΝ ΜΕΛΩΝ ΜΕ ΠΥΡΟΠΡΟΣΤΑΤΕΥΤΙΚΗ ΕΠΙΣΤΡΩΣΗ ΜΕ ΒΛΑΒΗ

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ΠΕΡΙΛΗΨΗ

Ο δομικός χάλυβας παρουσιάζει μείωση των μηχανικών ιδιοτήτων με την αύξηση της θερμοκρασίας, καθιστώντας απαραίτητη την λήψη μέτρων πυροπροστασίας των μεταλλικών δομικών μελών. Μια μέθοδος παθητικής πυροπροστασίας είναι η χρήση τσιμεντοειδών εκτοξευόμενων πυροπροστατευτικών υλικών (SFRM). Τα υλικά αυτά αν και διαθέτουν πολύ καλά πυροπροστατευτικά χαρακτηριστικά, έχουν χαμηλή μηχανική αντοχή με αποτέλεσμα να εμφανίζουν βλάβη όταν το δομικό μέλος υποστεί μηχανική παραμόρφωση. Συνέπεια αυτής της βλάβης είναι η μείωση του χρόνου πυραντοχής του δομικού μέλους. Για τη μελέτη του προβλήματος, αρχικά πραγματοποιείται αριθμητική μελέτη των μηχανισμών βλάβης της τσιμεντοειδούς πυροπροστατευτικής επίστρωσης μέσω προσομοίωσης του πειράματος κάμψης μεταλλικής πλάκας που φέρει πυροπροστατευτικό υλικό. Τα αποτελέσματα της ανάλυσης συγκρίνονται με τα πειραματικά δεδομένα, ώστε να επαληθευτούν οι μηχανισμοί αστοχίας και η ορθότητα της μεθόδου προσομοίωσης. Στη συνέχεια, πραγματοποιείται αριθμητική προσομοίωση κάμψης δοκού IPE που φέρει πυροπροστατευτική στρώση και μελετάται η βλάβη (αποκόλληση και ρηγμάτωση) που εμφανίζεται σ’ αυτή. Τέλος, διεξάγεται παραμετρική θερμική ανάλυση της δοκού, για διαφορετικό εύρος ρωγμής, υπό θερμική φόρτιση που αντιστοιχεί στην καμπύλη θερμοκρασίας – χρόνου ISO-834, και εξετάζεται η μεταβολή του χρόνου πυραντοχής της δοκού λόγω της ύπαρξης της βλάβης στην πυροπροστατευτική επίστρωση.