Fire Safety Journal 95 (2018) 42–50

Contents lists available at ScienceDirect

Fire Safety Journal

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

Experimental study of the performance of intumescent coatings exposed to standard and non-standard fire conditions

Andrea Lucherini [a,b,*], Luisa Giuliani [a], Grunde Jomaas [a,c]

[a] Department of Civil Engineering - DTU Byg, Technical University of Denmark (DTU), Denmark
[b] School of Civil Engineering, The University of Queensland, Australia
[c] School of Engineering, The University of Edinburgh, UK

ARTICLE INFO

Keywords:
Intumescent coatings
Thermal resistance
Heating rates
Standard and non-standard fire curves
Steel protection

ABSTRACT

Three different experimental setups corresponding to three different fire scenarios were used to investigate how different heating conditions and heating rates affect the behaviour of two different thin intumescent coatings (a solvent-based and a water-based paint). Coated steel samples were exposed to different standard and non-standard fire conditions in an electric oven, in a gas furnace and in a cone heater. A common trend was observed in the thermal resistance development of the tested coatings and three phases (inert phase, transient phase and steady phase) were identified according to four critical points: activation, end of reaction, binder exhaustion and steel austenitization point. The results also showed that the water-based paint performed better at low heating rates, while the tested solvent-based paint performed better at high heating rates and did not activate or provide proper insulation at very low heating rates. In summary, the study confirms that the current procedure for the design of intumescent coatings has shortcomings, as different paints have different performances according to the heating conditions and, in particular, according to the fire heating rate.

1. Introduction

Thin intumescent coatings (or reactive coatings) are nowadays the dominant passive fire protection system used to protect structural steel from fire. These coatings swell on heating to form a highly insulating foamed char, hence preventing steel from reaching critical temperatures that could cause structural failure. The increasing growth of intumescent coatings in the built environment is associated with the low impact in the attractive appearance of bare steel structure, with their ability to be applied off site and with their potential for offshore applications [1].

Intumescent coatings are thermally reactive fire protection materials and they are usually composed of a combination of organic and inorganic components bound together in a polymer matrix [2,3]. The composition can be solvent-based or water-based and they are usually applied with a dry film thickness (DFT) of about 2–3 mm.

According to current regulations, the fire resistance of an intumescent coating is based on compliance to standard fire resistance test [4,5]. Normally, manufacturers offer design tables that list the dry film thickness (DFT) of the product required in order to reduce the heat penetration for a specific structural steel member. This assessment method treats intumescent coatings as chemically non-reactive materials and it implicitly assumes that thermal properties only depend on the temperature. However, it is widely accepted that, unlike other non-reactive passive fire protective systems, the thermal properties of intumescent coatings are strongly affected by other conditions of any given fire event, for example the heating rate [2,3,6–8]. As a consequence, the current design procedures cannot be applied to other fire conditions due to the fire-dependent nature of these organic fire protection materials. Therefore, the standard fire exposure does not necessarily replicate the worst-case scenario and it does not represent a safe design.

Several studies have proposed various approaches and methodologies to analyse the performance of intumescent coatings exposed to different fire conditions. Anderson et al. developed a one-dimensional model to evaluate the effective thermal conductivity of the intumescent char [9]. Li et al. proposed a simple approach to assess the fire resistance of intumescent coatings and to predict the steel temperature using an equivalent constant thermal resistance [2,10]. Wang et al. evaluated the effective thermal conductivity of intumescent paints based on coated steel plates exposed to non-standard furnace fire curves [3]. Elliott et al. proposed a novel testing methodology for studying the performance of reactive coatings based on non-standard heating regimes [11]. Kolšek et al. implemented a semi-empirical procedure for performance-based

* Corresponding author. School of Civil Engineering, Advanced Engineering Building (#49), Staff Road House, The University of Queensland, St. Lucia, QLD, 4072, Australia.
E-mail address: a.lucherini@uq.edu.au (A. Lucherini).

https://doi.org/10.1016/j.firesaf.2017.10.004
Received 3 January 2017; Received in revised form 12 September 2017; Accepted 25 October 2017

calculations of intumescent painted steel members [12]. All presented simplified methods relate the insulating performance of intumescent paints to the applied coating thickness and the steel section factor only. However, Carpici et al. proposed the first example of a method that predicts the intumescent coating behaviour and the effective thermal conductivity also taking into account the fire conditions [8]. Despite the progress made in these studies, the performance of intumescent coatings subjected to different fire scenarios is still not fully understood due to the complexity of the intumescent process and the large range of different products and possible fire conditions.

In the current study, the insulating properties and behaviour of intumescent coatings exposed to eight different fire conditions were analysed. Steel samples coated by two commercial intumescent paints were tested in three different experimental setups, representing different types of heating regimes. The current study highlights the limits of the current design methodology and provides some suggestions for a safer design method accounting for the various aspects that affect the intumescent coatings insulating performance, such as the heating rate and heating conditions.

2. Experimental investigations

Two different types of specimens were used throughout the project. In the first and second sets of experiments, the test samples were IPE400 steel profiles, produced in specimens 400 mm long and with a resulting section factor A_s/V_s equal to 175 m^{-1}. In the third set of experiments, the test specimens were carbon steel plates of size 100 mm by 100 mm and 10 mm thick, with a resulting section factor A_s/V_s equal to 100 m^{-1}. All the samples were painted with either a solvent-based (Paint A) or a water-based (Paint B) intumescent coating, designed for applications on steel members. Both commercially available paints were professionally applied to a dry film thickness (DFT) of 1000 μm with an accuracy of ±100 μm (±10%). The applied dry film thickness was measured with a digital thickness gauge and the average measured DFTs are listed in Table 1.

Three different sets of experiments representing different types of heating exposure were conducted in order to study the behaviour and effectiveness of intumescent coatings under different fire conditions. All the conducted fire tests are outlined in Table 1 and the three different experimental setups are shown in Fig. 1.

2.1. Tests in electric oven

In this set of experiments, the intumescent coatings were tested in an electric oven with internal dimensions of the heating chamber of 72 × 82 × 97 cm (Fig. 1a). The oven was heated electrically and its temperature was monitored by a controller, setting a target temperature and a constant theoretical heating rate. One IPE400 steel profile sample per test was placed at half distance along the main axes of the oven in order to avoid large temperature differences. The specimen was placed in a horizontal position (column configuration) in order to study the behaviour of a steel profile cross-section orthogonal to the main component dimension. The steel samples were exposed to four non-standard fire curves with heating rates lower than the ISO 834 standard fire curve. The four temperature-time curves were characterised by different durations and heating rates, but similar target temperatures (about 900 °C). They were qualitatively denoted as “fast”, “medium”, “slow” and “very slow”, according to the heating rates. Thirteen coated specimens (four “very slow”, three “slow”, two “medium” and four “fast” – six with Paint A and seven with Paint B) and four unprotected

Table 1
Test matrix.

Sample ID	Specimen[(a)]	Section Factor [m^{-1}]	Paint[(b)]	Measured DFT [mm]	Test[(c)]	Fire Curve[(d)]
I03-A10-O.VS	I	175	A	1.17	O	VS
I07-A10.O.VS	I	175	A	1.28	O	VS
I04-B10-O.VS	I	175	B	0.95	O	VS
I06-B10-O.VS	I	175	B	0.89	O	VS
I01-U-O.VS	I	175	–	–	O	VS
I04-A10.O.S	I	175	A	1.07	O	S
I05-B10-O.S	I	175	B	0.92	O	S
I07-B10-O.S	I	175	B	0.90	O	S
I02-U-O.S	I	175	–	–	O	S
I02-A10-O.M	I	175	A	1.22	O	M
I02-B10-O.M	I	175	B	0.95	O	M
I03-U-O.M	I	175	–	–	O	M
I05-A10-O.F	I	175	A	1.15	O	F
I06-A10-O.F	I	175	A	1.19	O	F
I03-B10-O.F	I	175	B	0.92	O	F
I08-B10-O.F	I	175	B	0.90	O	F
I04-U-O.F	I	175	–	–	O	F
I08-A10-F.ISO	I	175	A	1.15	F	ISO
I09-A10-F.ISO	I	175	A	1.31	F	ISO
I09-B10-F.ISO	I	175	B	0.95	F	ISO
I10-B10-F.ISO	I	175	B	0.90	F	ISO
I05-U-F.ISO	I	175	–	–	F	ISO
P38-A10-C.20	P	100	A	1.10	C	20
P31-B10-C.20	P	100	B	1.09	C	20
P01-U-C.20	P	100	–	–	C	20
P44-A10-C.40	P	100	A	1.02	C	40
P35-B10-C.40	P	100	B	1.00	C	40
P02-U-C.40	P	100	–	–	C	40
P43-A10-C.60	P	100	A	1.09	C	60
P32-B10-C.60	P	100	B	1.03	C	60
P03-U-C.60	P	100	–	–	C	60

[(a)] Specimen: I = IPE400 steel profile section; P = steel plate 100 × 100 × 10 mm;
[(b)] Intumescent paint: A = Paint A; B = Paint B.
[(c)+(d)] Test + Fire Curve: O = electric oven [VS = very slow, S = slow, M = medium, F = fast].
F = gas furnace [ISO = standard ISO]; C = cone heater [20 = 20 kW/m^2, 40 = 40 kW/m^2, 60 = 60 kW/m^2].