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FIBRE-REINFORCED EPOXY INTUMESCENT COATINGS FOR STRENGTHENING AND FIRE PROTECTING STEEL BEAMS

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ABSTRACT: Epoxy intumescents are reactive polymer coatings used for fire protection of steel structural elements, commonly in offshore oil and gas applications, amongst others. These materials react and expand to form an insulating char layer when heated, thus protecting underlying steel from fire. Thick-film fibre-reinforced epoxy intumescents are a special class of such coatings that are extensively used in offshore and industrial facilities to provide protection against hydrocarbon and jet fires; their durability to harsh environmental exposure and mechanical damage are essential in these applications. To enhance the stability and integrity of these coatings continuous fibre reinforcement is typically embedded within the polymer coating. However, designers currently assume that the presence of this fibre reinforcement is only a means of strengthening and maintaining the integrity of expanding fire protective char during fire exposure; the structural contribution of the fibre reinforcement at ambient temperature is ignored. The coating remains in an unreacted state for the majority of its life until a possible fire, and is essentially a fibre-reinforced polymer composite intumescent coating (FRIC). In reality, this coating has strength and stiffness which may actually enhance the ambient performance of the underlying structure. This paper examines, for the first time, the mechanical performance of an epoxy-based intumescent coating with varying amounts of internal fibre reinforcement through a series of uniaxial tensile tests. Experiments are presented on the flexural behaviour of coated steel I-sections protected with two subtly different intumescent systems. The data demonstrate the potential ambient temperature mechanical benefits of FRICs applied to structural steelwork, which are often neglected by designers.

1. Introduction and Background

Intumescent coatings are reactive polymer coatings that are widely used as a means of protecting structural steel elements from fire. When exposed to heat, they react and expand into a thick char layer with low thermal conductivity, thus insulating the steel substrate to which they are applied. They generally consist of a char-forming (carbonific) material, a catalyst, a blowing agent (spumific), a binder and various other fillers (Weil, 2011). Thick film epoxy-based intumescent coatings are extensively used in offshore installations and industrial facilities to provide fire protection of steelwork against hydrocarbon pool and jet fires, as well as offering corrosion protection. In these applications the durability to harsh environmental exposure and damage resistance of the epoxy binder are essential. The typical thickness of these coatings ranges between 5 and 25 mm, and depends on the required fire resistance, the steel section type and section factor (the ratio of heated surface area to volume of steel) and the limiting temperature adopted in design, typically based on design code requirements (Lennon and Hopkin, 2012). For fire scenarios that are credible threats in oil and gas applications, the fire protection coatings must resist highly erosive forces from ignited pressurised gases, as well as comparatively high imposed heat fluxes (HSE, 1992). In addition to highly insulating properties a fire protection coating must maintain its integrity during exposure to fire. To enhance the fire performance (char integrity) of intumescent coatings, continuous fibre reinforcement is often embedded within the polymer coating using a bidirectional carbon and/or glass fibre mesh. This mesh strengthens and maintains the integrity of the otherwise comparably weak char during expansion in fire. The coating remains in its unreacted state for the majority of its life and is essentially a lightly fibre-reinforced intumescent coating (FRIC). Such coatings have a long track record and their thermal and physicochemical properties have been studied extensively; however it appears that no information is available on their mechanical behaviour at ambient temperature and in particular on their impacts on the structural response of coated elements under normal conditions.

This paper presents an initial investigation into the mechanical performance and structural impacts of two commercially available FRICs, with varying amounts of internal fibre reinforcement. Similar research has been undertaken previously with a view to increasing the strength and/or stiffness of structural steel elements using high modulus carbon FRP strengthening systems (e.g. Colombi and Poggi, 2006), however this has never before been studied using intumescent epoxies to provide strengthening *in addition to* fire protection. A series of uniaxial tensile tests are presented on coupons reinforced with different volume fractions of hybrid carbon/glass or pure carbon fibre mesh. The flexural behaviour of steel I-sections protected with the coatings is subsequently presented to investigate the contributions of the composite materials on the structural response of the steel beams and the potential of using these materials to provide a system for combined strengthening and fire protection of deteriorated steel elements.

2. Materials Characterization

2.1. Tensile Testing

The matrix of tests for mechanical characterization of the coatings is presented in Table 1. Two commercially available epoxy intumescent coatings were examined in the current study (these are referred to as Coatings A and B). Two different reinforcement meshes were also used; a light mesh (Mesh 1) consisting of carbon and glass rovings, either as a single layer or in three stacked layers, and a heavyweight carbon mesh (Mesh 2). A unidirectional carbon fibre fabric was also used to study the tensile response at intermediate fibre volume fractions. Two versions of this fabric were tested: one as-supplied (Fabric 1B) and one with rovings manually removed (Fabric 1A) for a mesh with half the fibre weight.

Table 1 – Testing matrix and selected results of tensile testing on various FRICs

Material	Fibre reinforcement type	Carbon fibre volume fraction (%)	Tensile strength (MPa)			Elastic modulus (MPa)			Failure strain (%)	
			Mean	Std dev.	% Gain	Mean	Std dev.	% Gain	Mean	Std dev.
Coating A	Plain	0	6.34	1.01	–	983	53	–	0.69	0.14
	Mesh 1[a]	0.09	8.03	0.69	27	1122	107	16	0.90	0.09
	Mesh 1, ×3[b]	0.27	9.45	0.39	49	1248	60	29	0.92	0.07
	Fabric 1A[c]	0.57	15.00	1.20	136	1879	89	95	0.89	0.15
	Fabric 1B[d]	1.14	31.65	1.67	399	3069	260	218	1.23*	0.23
	Mesh 2[e]	1.35	26.12	1.71	312	3730	187	286	0.66*	0.03
Coating B	Plain	0	10.80	0.78	–	914	52	–	2.44	0.18
	Mesh 1[a]	0.09	13.98	1.17	29	1372	70	50	1.52	0.07
	Mesh 1, ×3[b]	0.27	16.44	0.95	52	1390	147	52	1.42	0.07
	Fabric 1A[c]	0.57	28.11	1.53	160	1883	89	106	1.54	0.13
	Fabric 1B[d]	1.14	41.23	4.67	282	3127	178	241	1.31	0.15
	Mesh 2[e]	1.35	41.31	0.87	282	3642	246	298	1.14	0.05

[a] orthogonal carbon and glass mesh; equivalent total carbon weight in warp direction (wrt stiffness): 18 g/m^2
[b] three layers of Mesh 1 stacked and offset on top of each other at the coating mid-thickness
[c] unidirectional carbon fibre fabric; alternate rovings removed; weight 115 g/m^2
[d] unidirectional carbon fibre fabric; weight 230 g/m^2
[e] orthogonal carbon fibre mesh; weight 282 g/m^2 in warp direction
* DIC strain values for these specimens are unreliable due to localised cracking of the matrix

Coupon samples were cast in 300 mm square, 10 mm thick panels with the fibre reinforcement placed at mid-thickness. Panels were cured at ambient temperature in the lab for two weeks and then post-cured for 24 hours at 80°C according to the manufacturer's specifications. Five rectangular specimens with dimensions 300×50×10 mm were cut from each panel and tested in an Instron 600LX universal testing machine at a crosshead displacement rate of 1 mm/min. Specimen dimensions were chosen such that the thickness (and fibre volume fraction) were realistic and representative of typical applications, and so that the width was the maximum possible within the wedge action grips to accommodate as many mesh

cells per unit width as possible. Strain measurements were made optically using a Digital Image Correlation (DIC) technique implemented with a high resolution digital camera and the GeoPIV software code developed by White et al. (2003). Images were captured at a rate of 0.2 Hz, which in general may affect the accuracy of the measured failure strain; for the purposes of this study this is considered adequate.

2.2. Tensile Test Results

Selected results of the tensile tests are presented in Table 1. The typical observed stress-strain responses (in this case for Coating B) are given in Figure 1. Similar responses and scatter were observed for Coating A, however the strain data for higher fibre contents were of comparatively low quality due to localized cracking of the epoxy, leading to problems with confident use of the DIC strain measurement technique. In both cases, coupons made from unreinforced coatings were characterised by a non-linear stress-strain response, which gradually transitioned to linear with increasing fibre contents. The primary difference in the mechanical response of the two polymers was their respective unreinforced failure strains, and this governed the failure mode of the respective fibre reinforced specimens. The failure strain of the unreinforced polymer Coating A (matrix only) was lower than that of the carbon fibre reinforcement, and as a result the fibre reinforced coupons failed as soon as the epoxy failure strain was reached for samples with lower fibre volume fractions. For fibre volume fractions higher than 1.14% (i.e. for Fabric 1B and Mesh 2 with Coating A) the fibres were able to carry load after cracking of the matrix; however due to DIC strain measurement problems after cracking reliable ultimate strain values could not be determined for these specimens. Conversely, unreinforced Coating B was characterised by a larger failure strain than the reinforcing fibres, which resulted in their full utilisation up until tensile fracture.
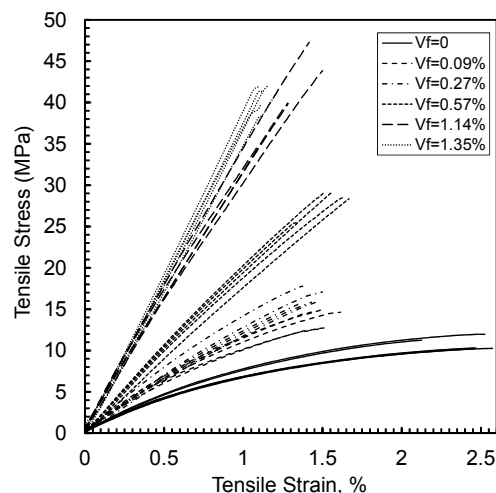

Figure 1 – Typical stress-strain responses observed for various FRICs (Coating B)

The variation of the tensile stress and elastic modulus with fibre volume fraction and the predictions by the rule of mixtures (RoM) are shown in Figure 2. As expected, an increase in the fibre volume fraction increases both the ultimate tensile strength and the elastic modulus for both coatings. In general, Coating B is characterized by higher failure stresses and strains, and therefore by better fibre utilization as discussed previously; this is a consequence of Coating B's higher unreinforced failure strain and is corroborated by a simple rule of mixtures prediction (included in Figure 2). Whilst the presented tensile stresses appear low in comparison to steel, it is important to recognize that this is an artefact of the unusually large thickness of epoxy used, as compared with more traditional FRP structural strengthening systems; clearly this thickness is dictated by fire protection requirements rather than structural strengthening considerations. Both coatings see no significant increase in tensile strength with fibre volume fraction increases from 1.14 to 1.35%, however the reasons for this are not yet known. It may be that the differences in fibre architecture (i.e. unidirectional versus bi-directional mesh) play a role in the overall composite performance. Additional testing would be required to investigate this hypothesis.
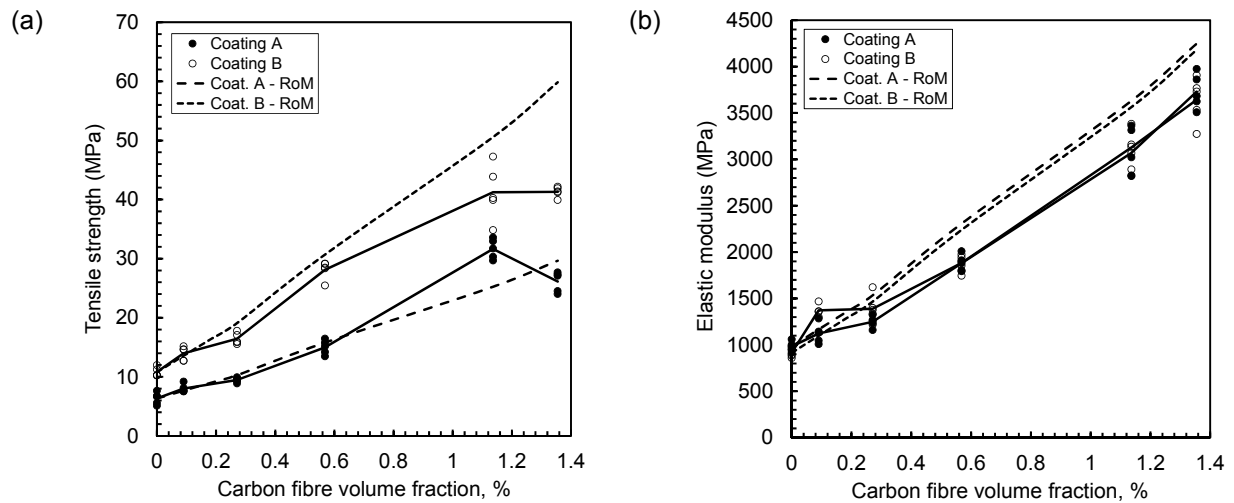
Figure 2 – Observed variations in (a) ultimate tensile strength and (b) tensile elastic modulus of FRIC coupons with varying fibre contents, including theoretical predictions by rule-of-mixtures

3. Strengthened/Protected Steel Beam Tests

3.1. Experimental Procedure

The experimental program for the beam tests is given in Table 2 and comprised three simply-supported flexural tests of steel I-sections; one of these was a plain steel reference specimen (i.e. unprotected/unstrengthened), one was protected/strengthened with 10 mm of carbon fibre reinforced Coating A, and the third was protected with 10 mm of carbon fibre reinforced Coating B. Both protected beams' coatings were internally reinforced with Mesh 2, only around the beam flanges. The steel sections used were UKB 203×133×25 and were 3000 mm long. At the time of writing this paper, steel coupon tests had not yet been performed to obtain the true steel yield strength; however the yield strength was estimated from indentation hardness tests to be 438 MPa (an average Vickers Pyramid Number 184). The beams were prepared by blast cleaning to a Sa2½ standard (ISO 8501-1, 2007) and primed with an industry-standard epoxy primer which is used by the intumescent coating supplier in actual field applications of these coatings. The coatings were applied by trowel application in two layers, and a single layer of carbon fibre mesh (Mesh 2) was embedded at the mid-thickness of the coating around each flange. No fibre reinforcement was included within the coating over the beams' webs. The coating was terminated at 50 mm from each support point to prevent pinching of the FRIC at the support points.

The test setup and instrumentation arrangement for the beam tests is shown in Figure 3. Specimens were loaded in four-point bending using a 250 kN Instron 8800 hydraulic actuator at a crosshead displacement rate of 3 mm/min. To avoid lateral-torsional effects, lateral restraints (i.e. fork supports) were used at support locations (refer to Figure 2). Intermediate bracing could not be provided for the beams because of the presence of the coatings; instead the actuator was braced (restrained) laterally to minimise out of plane movements of the beam in an attempt to prevent lateral-torsional buckling failure. For the same reason, the use of intermediate stiffeners was avoided because this would obstruct the longitudinal continuity of the carbon fibre mesh reinforcement. The practical issues associated with a need to maintain fibre continuity around stiffeners in real applications of these coatings will be considered in future work.

Vertical displacements of the beams were recorded with linear potentiometers and DIC. Strains were measured at midspan and at the end of the bond line using foil gauges (along with DIC at midspan, not included in this paper). Data was acquired and logged at a rate of 10 Hz (0.2 Hz for DIC data).

Table 2 – Test matrix and selected experimental results for FRIC-strengthened steel I-section tests

Specimen	Flexural stiffness (kN/m)	% Gain	Yield load (kN)[a]	% Gain	Predicted yield load (kN)[b]	% Gain	Peak load (kN)	% Gain	Deflection at peak load (mm)
Plain steel	8321.6	–	141.3	–	159.2	–	171.7	–	30.9
Coating A	8926.8	7.3	148.2	4.9	161.6	1.5	195.1	13.6	53.2
Coating B	8836.7	6.2	147.5	4.4	162.4	2.0	189.3	10.3	45.2

[a] defined on the basis of a 0.2% deflection offset
[b] strain compatibility and cross-sectional equilibrium analysis
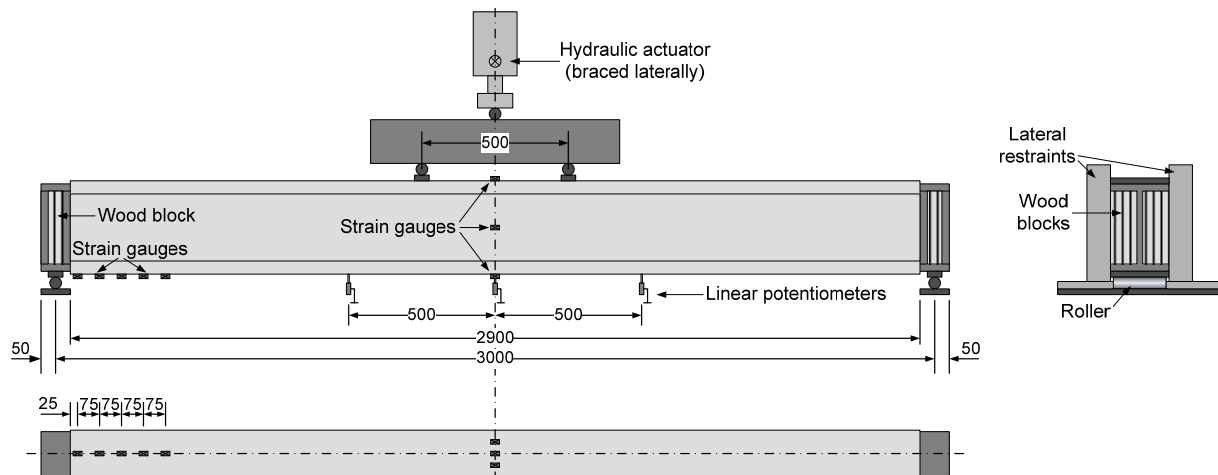

Figure 3 – Schematic showing beam test setup and instrumentation

3.2. Beam Test Results

Selected results of the beam tests are given in Table 2 and Figure 4. Also included in Table 2 and Figure 4(b) are theoretical predictions for predicted yield load (defined on the basis of a 0.2% deflection offset) and predicted load versus bottom flange tensile strain response (using a strain compatibility and cross-sectional equilibrium analysis assuming full bond between beam and coating).

All three beams failed by local buckling of the top flange in compression, underneath one of the loading points. This appeared to be instigated by slight lateral-torsional displacements of the beams. The unstrengthened beam achieved loads very close to full plastification of the cross section (refer to Figure 4(b)), whereas the strengthened beams demonstrated enhanced performance due to the effectively linear-elastic stress-strain response of the FRICs.

The data in Table 2 show that significant increases in both strength and stiffness of the beams were realized for both Coatings A and B. Flexural stiffness was enhanced by about 7.3 and 6.2%, whereas yield strength was enhanced by 4.9 and 4.4%, for Coatings A and B, respectively. Peak load enhancement was more substantial, at 13.6 and 10.3%, respectively, indicating strong potential for FRICs to be explicitly considered during the structural design of FRIC-protected steel elements; this could potentially permit reductions in steel section thickness, with knock-on benefits of weight reduction, reduced carbon footprint, and structural optimization. Figure 4(a) shows the enhanced load deflection response of the protected versus unprotected steel beams. Enhancements in strength and stiffness, particularly post-yield stiffness, are apparent. Furthermore, Coating A appeared to provide a slightly superior enhancement, however additional tests are required to corroborate this observation. The FRICs also improved the deformability of the beams by preventing lateral-torsional displacement and local buckling of the top flange under the loading points. Figure 4(b) shows that a simple plane-sections, cross-sectional equilibrium analysis is able to accurately predict strains in the FRICs during loading. The theoretical predictions in Figure 4(b) neglect lateral torsional effects, and therefore over-predict the achievable deflections of all beams. Finite element modelling is currently underway in an attempt to account for stability effects on load-displacement response.
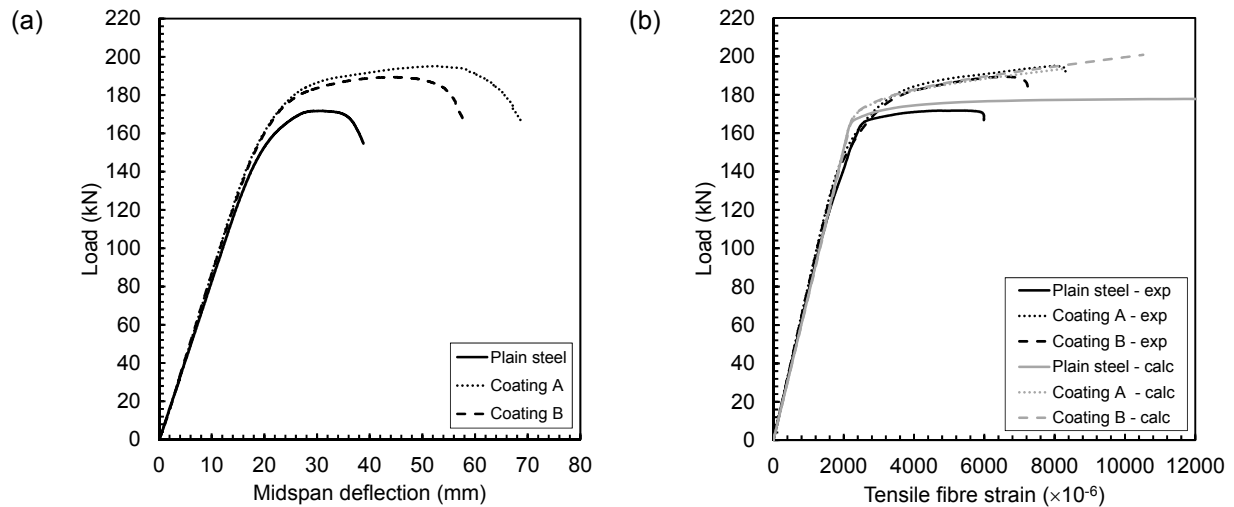
Figure 4 – (a) Observed load versus midspan vertical deflection and (b) Observed and predicted load versus tensile fibre strain at midspan for FRIC-strengthened steel I-sections

4. Conclusions

The preliminary experimental study presented in this paper has demonstrated that:

- the tensile mechanical properties (both strength and stiffness) of FRICs can be significantly enhanced by the inclusion of increasing amounts of carbon fibre reinforcement during coating application; the enhancement of properties can be predicted by a rule-of-mixtures approach.

- the yield strength, flexural stiffness, and ultimate load carrying capacity of steel I-sections in bending can be significantly enhanced by coating the beam with a FRIC system; ultimate strength enhancements in the range of 13% are possible (utilizing more than 45% of the carbon fibres' ultimate strain capacity for the tests presented herein).

- the structural response of FRIC-strengthened steel I-sections in bending can be satisfactorily predicted using a simple plane-sections analysis assuming perfect bond between the coating and the beam; however additional research is needed to understand the influence of the coatings on failure modes initiated by local and/or lateral-torsional buckling.

5. Acknowledgements

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