# ACCEPTANCE CRITERIA FOR DAMAGED AND REPAIRED PASSIVE FIRE PROTECTION

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## INTRODUCTION

The performance of ageing, weathered, damaged or repaired passive fire protection (PFP) is a major concern, particularly offshore where it is often a safety-critical factor in protecting structures and plant from the effects of severe fires. The two most commonly used types of PFP materials are cementitious and intumescent. Cementitious PFP works initially by holding the temperature of the substrate to around 100°C until all the bound water is vaporised and then acts as a passive insulator. Intumescent PFP has an organic base which, when subjected to fire, expands producing a stable char with good thermal insulation properties.

Whilst the performance of these materials when in good condition is well understood, little or no information is available which provides an understanding of their performance in a damaged or repaired state. In the absence of such information, verifying performance standards where PFP is employed as a risk-reduction measure cannot be undertaken reliably.

To address this shortfall, a two-phase Joint Industry Project was established to develop data on the performance of damaged PFP and to suggest an inspection methodology with acceptance criteria. This paper will describe specially produced damaged and repaired PFP test pieces (both cementitious and intumescent) and will summarise their performance in jet fire resistance tests.

The paper will also discuss the acceptance criteria developed for damaged and repaired PFP. The project's findings are providing important input into a new procedure for identifying when repair or replacement is necessary, and which forms of repair are most effective. The findings also highlight valuable lessons in quality assurance of the PFP application process.

The work reported here was undertaken in a collaborative project developed and managed by MMI Engineering Ltd. The work was sponsored by HSE, BP, Centrica

 

Energy, Canadian Natural Resources, Marathon, Total, and Shell. PFP materials were provided by International Coatings, Cafco International, and PPG Indistries, and specimen coating was undertaken by Salamis and RBG Ltd. Testing was undertaken on behalf of the Sponsors by the HSL.

## TEST FACILITY AND INSTRUMENTATION

The tests were carried out using HSL's jet fire resistance test facility. The facility is designed to give an indication of how well passive fire protection materials will perform in a jet fire. It involves impinging a propane vapour jet fire on a target covered with PFP material. The test facilities and details comply with OTI 95 634 and Draft ISO standard ISO/CD 22899-1.

The test specimen was bolted between an open-fronted steel box (lined with ceramic boarding) and a protective rear chamber. A wall of lightweight building blocks was erected around the target assembly to prevent flames impinging on the sides of the target. A photograph showing the installed assembly is given in Figure 1.

The test specimen was instrumented with mineral insulated, stainless steel sheathed, 1.5 mm, type K thermocouples supplied and fitted by HSL. Thermocouples were installed in the back surface of the panels by means of drilled, interference fit, holes and were held in position in the web by bulkhead fittings. Measurements were logged using DT3003 32 channel Data Translation data acquisition boards fitted directly into a PC. A FLIR SC 2000 thermal imaging camera was used to measure the temperature distribution over the back of the test specimen.

## SUBSTRATE

The substrate for a normal structural steel test consists of an open-fronted steel box, nominal internal dimensions 1500 mm × 1500 mm × 500 mm, made from 10 mm thick steel.

**Figure 1.** Installed Assembly (test 10 specimen, before test)

 

It has a 20 mm thick central web, 250 mm deep, to simulate corner or edge features such as stiffening webs or edges of “I” beams. The web is made up of two 10 mm thick steel plates, which are slotted before being welded together, to allow the insertion of thermocouples The box is flanged at the rear to allow attachment (by bolting or clamping) of a 1500 mm × 1500 mm × 1000 mm protective chamber when required.

In order to be able to test as many types of damage as possible, whilst keeping the number of jet fire tests to a minimum, it was decided to replace the back of the box with a panel comprising two half panels and a web. In this way, three different features could be assessed in each test. A piece of L-section was welded along the back of one edge of each of the half panels and holes drilled through these and the back of the web to allow the two half panels and the web to be bolted together (see Figure 2).

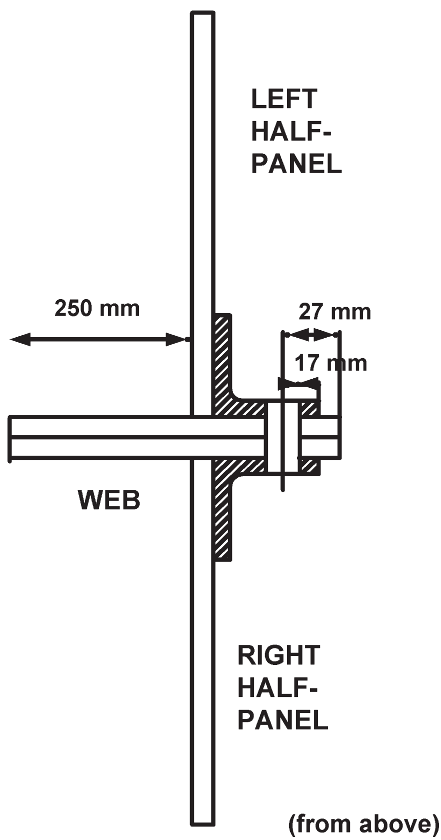


**Figure 2.** Half-Panel and Web Assembly

 

For the repair trials, it was considered that the number of joints should be minimised by welding the half panels and the web together to give a single panel incorporating the web. A second type of substrate was also used. This consisted of a simple plate panel, without a web, fitted to form the back of the box.

## COATING

Test specimens for the damage trials were coated with cementitious or intumescent PFP materials supplied by Cafco International (Mandolite 550), International Coatings (Chartek IV and VII) and PPG Industries (Pitt-Char XP).

Specimens were coated with the required thickness of each material (as specified by the manufacturer) to achieve the following protection criteria, when subjected to a jet fire test:

Panels – at least 60 minutes for a temperature rise of 140°C.
Web – at least 60 minutes for a temperature rise of 400°C.
(temperature rise above initial substrate temperature)

Chartek IV is a relatively hard epoxy intumescent PFP material and Pitt-Char XP is a softer, more flexible material. A thickness of 12 mm of the respective intumescent materials was applied to the panels and webs, with reinforcement located in the middle third of the coating.

The cementitious test specimens were all prepared with a nominal 38 mm deep coating of Mandolite 550. Reinforcement was with plastic coated hexagonal wire mesh retained by helical pins in the middle third of the coating.

The repair test specimens were coated with a combination of cementitious material (Mandolite 550) and intumescent material (Chartek VII or Pitt-Char XP). These particular intumescent materials were chosen as both can be used with reinforcement that does not require pinning.

Coating of the majority of the substrates was witnessed and quality controlled by MMI Ltd. A photograph illustrating coating of a repair test specimen is provided in Figure 3.

## TEST PROGRAMME

The first test series involved carrying out jet fire resistance tests on PFP specimens with the following types of induced damage:

- Gouges and nicks;
- Cracks;
- Loss of bonding and retention; and
- Water saturation (cementitious specimen)

The second test series was designed to test several typical 'in-situ' repairs found offshore. In practice, where damage has occurred to a small area of cementitious material, it is typically

 

**Figure 3.** Coating Application – Butt joint

removed and replaced with new intumescent material. Problems can arise at the interface between the materials, as the two types of PFP work by completely different mechanisms.

Three types of repair joint were investigated:

- Simple butt joints between the cementitious and intumescent PFP;
- Two step cementitious/intumescent joints; and
- A smooth chamfer joint between the materials

The induced damage and repair joints are described in more detail in Tables 1, 2 and 3. The joints are also illustrated in Figure 4.

## RESULTS AND CONCLUSIONS

The most significant results and overall conclusions from the damage and repair trials are detailed below. The results from this collaborative project will also be accessible, via the HSE website, in due course.

## DAMAGED INTUMESCENT TRIALS

### RESULTS

Figures 1 and 5 show the specimen for trial 10 before and after testing. The purpose of this test was to determine the effect of gouging, cracking and disbondment on Chartek IV.

Left Panel

The left panel was physically damaged (gouged), but was bonded to the steel substrate. After the test, slight enlargement of the gouges was observed. Thermocouple temperatures and thermal images confirm that the main hot spot was recorded behind the horizontal

 

**Table 1.** Intumescent PFP tests

| Test number | Purpose | Anomalies |
|---|---|---|
| 01 | Chartek IV control specimen | None. Panels and web all with same thickness (12 mm) of sound material and reinforcement |
| 02 | Effect of loss of material, to depth of reinforcement layer, and beyond on Chartek IV | Left panel – Sound material with 350 mm × 40 mm vertical gouge to depth of reinforcement.<br>Right panel – Sound material with 350 mm × 40 mm vertical gouge beyond depth of reinforcement.<br>Web – 350 mm long vertical 45° nick from edge of web beyond depth of reinforcement. |
| 04 | Chartek IV disbonding | Left panel – Disbonded with partially retained mesh.<br>Right panel – Bonded with no mesh<br>Web – Disbonded with partially retained mesh |
| 10 | Effect of gouging, cracking and disbondment on Chartek IV | Left panel – Sound material with 200 mm × 25 mm horizontal gouge in top half, 200 mm × 12 mm horizontal gouge in bottom half and 350 mm × 12 mm vertical gouge running downwards from centre. All gouges through mesh.<br>Right panel – Disbonded material with 2, 3 and 5 mm cracks to substrate running full length.<br>Web – Disbonded material with 5 mm crack to substrate running full length. |
| 13 | Effect of gouging, cracking and disbondment on Pitt-Char XP | Left panel – Sound material with 200 mm × 25 mm horizontal gouge in top half, 200 mm × 12 mm horizontal gouge in bottom half and 350 mm × 12 mm vertical gouge running downwards from centre. All gouges through mesh.<br>Right panel – Disbonded material with 2, 3 and 5 mm cracks to substrate running full length.<br>Web – Disbonded material with 5 mm crack to substrate running full length. |

(25 mm × 200 mm) gouge above the centre line. The time until a 140°C temperature rise was seen behind this gouge was 4 minutes. The highest temperature rise after 60 minutes was 325°C.

Right Panel

Prior to the test, the right panel was cracked and the coating was deliberately disbonded from the steel substrate. After the test this panel was much more damaged than the left

 

**Table 2.** Cementitious PFP tests

| Test number | Purpose | Anomalies |
|---|---|---|
| 05 | Control specimen | None. Panels and web all with same thickness (38 mm) of sound material, and reinforcement |
| 06 | Effect of loss of material, to depth of reinforcement layer, and beyond | Left panel – Sound material with 350 mm × 40 mm vertical gouge to depth of reinforcement.<br>Right panel – Sound material with 350 mm × 40 mm vertical gouge beyond depth of reinforcement.<br>Web – 350 mm vertical nick from edge of web beyond depth of reinforcement. |
| 07 | Effect of cracking | Left panel – Sound material with 1, 3 and 5 mm cracks running full length.<br>Right panel – Disbonded material with 1, 3 and 5 mm cracks running full length.<br>Web – Disbonded material with 5 mm crack running full length. |
| 08 | Effect of moisture content | Left panel – Sound material with panel fully saturated.<br>Right panel – Sound material with panel 50% saturated.<br>Web – Sound material with web fully saturated. |
| 09 | Effect of loss of bonding and loss of retention | Left panel – Disbonded material & steel reinforcement fixed around edges of panel.<br>Right panel – Bonded material with no steel reinforcement.<br>Web – Disbonded material and steel reinforcement partially retained. |

panel (above), the material was bowed out from the substrate and cracked. There was considerable enlargement of the induced cracks, particularly the 2 mm crack. The highest temperatures were recorded at the lower ends of the cracks, in the high erosion zone. Thermal images confirm that there is a hot area around all three cracks in the high erosion zone. The time until a 140°C temperature rise was seen behind the cracks was 9 minutes. The highest temperature rise after 60 minutes was 262°C.

Web

The web was physically damaged (cracked) and the coating was deliberately disbonded from the steel substrate. Temperatures rose very rapidly behind the (5 mm) crack on the web. Major damage was caused, with bare steel being exposed for the bottom two thirds of the web. A 400°C temperature rise was achieved after 5 minutes. The maximum temperature rise of 705°C was achieved after 25 minutes, with the temperature rise at 60 minutes being 656°C. These temperatures are consistent with the Chartek IV being stripped off leaving bare steel exposed to the jet fire.

 

**Table 3.** Repair tests

| Test number | PFP | Repair |
|---|---|---|
| 03 | Mandolite 550 with hexagonal wire mesh reinforcement repaired with Chartek VII with HK-1 glass/carbon fibre reinforcing scrim | Simple butt joint vertically and horizontally in a panel without a web |
| 11 | Mandolite 550 with hexagonal wire mesh reinforcement repaired with Chartek VII with HK-1 glass/carbon fibre reinforcing scrim | Left panel – Stepped cementitious joint across centre line.<br>Right panel – Chamfered intumescent joint across centre line.<br>Web – Stepped cementitious joint on left side and chamfered intumescent joint on front and right side of centreline. |
| 12 | Mandolite 550 with hexagonal wire mesh reinforcement repaired with Pitt-Char XP with FM glass fibre reinforcing scrim | Left panel – Stepped cementitious joint across centre line.<br>Right panel – Chamfered intumescent joint across centre line.<br>Web – Stepped cementitious joint on left side and chamfered intumescent joint on front and right side of centreline. |

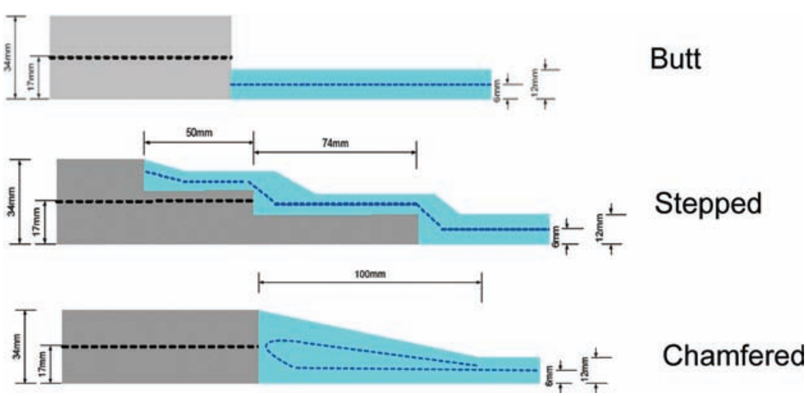


**Figure 4.** Repair joints

 

**Figure 5.** Specimen for test 10 (after test)

## CONCLUSIONS

The main conclusions from the damaged intumescent trials were as follows:

(a) If there is a gouge in PFP on a panel, a hot spot is formed behind it in a jet fire. If the gouge is down to the substrate, 12 mm and 25 mm wide gouges give a 140°C temperature rise within 3 minutes and a 75 mm wide gouge gives a 400°C temperature rise within the same time. The temperature rise is slower if the gouge leaves PFP attached to the substrate (22 minutes until 140°C temperature rise on 75 mm gouge with material remaining.

(b) 45° nicks in PFP on webs lead to bare metal being exposed in a jet fire. Where the nick just exposed the substrate, a 400°C temperature rise was reached in 30 to 36 minutes and where the nick just exposed the mesh, in 46 minutes. The evidence suggests that the erosive forces shear off the char if it expands at right angles to them.

(c) A 5 mm crack in disbonded material has a much more severe effect on material on an edge feature (web) than on a flat surface (panel). A crack in the PFP on an edge leads to rapid failure of the PFP with the PFP being stripped off leaving bare metal and giving a temperature rise of 400°C within 4 minutes. This occurs with both Chartek IV (a relatively hard material) and Pitt-Char XP (a relatively soft material) and hence it is likely to occur with any epoxy intumescent material. Cracks in disbonded material on flat surfaces still lead to considerable damage with a temperature rise of 140°C occurring within 10 minutes, with the Pitt-Char XP being more effected than the Chartek IV.

(d) For the material on the panels, disbondment (with partially retained reinforcement mesh) and a complete lack of reinforcement appear to have only a minor effect on fire resistance, with lack of reinforcement having a marginally greater effect (58 minutes for a temperature rise of 140°C compared to greater than 60 minutes). However, as indicated above, if there are flaws in the surface of the material, this can lead to rapid failure. There appeared to be a slightly greater effect on the disbonded material with partially retained reinforcement on the web with a temperature rise of 400°C in 55 minutes rather than the required 60 minutes.

(e) Precise specification and quality control of intumescent PFP application (material thickness, uniformity, reinforcement position) is required in order to achieve the desired level of fire protection from the PFP.

SUMMARY

The overall conclusions are that the most severe effects are from damage to PFP on edges. Cracks in disbonded material lead very rapidly to the PFP being stripped off and nicks can give the same effect although it takes longer. For material on flat surfaces, gouges or cracks down to the substrate lead to a significance loss in fire resistance, particularly if the material is also disbonded. Disbondment or loss of reinforcement alone, (no surface damage) has only a minor effect on performance provided that the material is at least partially attached to the surface (by the reinforcement system if disbonded or by the bonding if the reinforcement system is corroded).

## DAMAGED CEMENTITIOUS TRIALS

RESULTS

Figures 6 and 7 show the specimen for trial 07 before and after testing. The purpose of this test was to determine the effect of cracking and disbondment on Mandolite 550.

**Figure 6.** Specimen for test 07 (before test)

 

**Figure 7.** Specimen for test 07 (after test)

Left Panel

The left panel was physically damaged (5, 3 and 1 mm induced cracks), but was bonded to the steel substrate. On completion of the test, the dimensions of the cracks remained unchanged. The highest temperature rise of 166°C after 60 minutes was recorded at the top of the 5 mm crack.

Right Panel

The right panel was also physically damaged (5, 3 and 1 mm induced cracks). In addition, the coating was deliberately disbonded from the steel substrate. On completion of the test, the dimensions of the cracks remained unchanged but, in this case, the coating bowed out from the substrate in the bottom two-thirds of the panel. The highest temperature rise of 222°C after 60 minutes was recorded at the bottom of the 5 mm crack.

The thermal image at 60 minutes suggested that the whole of the right hand panel (with cracked, disbonded material) was hotter than the left panel (with cracked, bonded material). This may account for the coating bowing out from the substrate.

Web

The web was physically damaged (cracked) and the coating was deliberately disbonded from the steel substrate. Initially the web temperatures around the high erosion positions were higher than the temperatures in the high heat flux positions. Towards the end of the test the temperature at the centre of the web in the high heat flux zone exceeded the others. Bare metal was visible behind mesh on 95% of front face of the web and on the sides of the web; the PFP material was (mainly) intact but coming away from the substrate, due to the erosion forces from the jet. If the reinforcement had not been intact, it is likely that the PFP would have fallen off. A full-depth crack was observed along the width of the web at the bottom right hand side. The highest temperature rise after 60 minutes was 473°C behind the middle of the 5 mm crack on the web.

## CONCLUSIONS

The main conclusions from the damaged cementitious trials were as follows:

(a) 350 mm × 40 mm gouges on flat surfaces resulted in slightly higher temperatures if the gouge was through the retention mesh rather than down to the mesh although the damaged panels still both easily met the 140°C temperature rise in greater than 60 minute fire resistance requirement. The 350 mm long 45° nick in the web gave much higher temperatures than an undamaged specimen but still met the 400°C fire resistance criterion. Gouges and nicks of the size used would not result in failure, although the safety margin is lower for a nick on an edge feature.

(b) For the specimens with 1, 3 and 5 mm cracks, cracks in sound material were less serious than those in disbonded material. None of the cracks increased in size, probably because the retention mesh was intact. It is likely that the PFP on the web would have fallen off if the retention mesh had been corroded by water ingress. Cracks in sound material reduced the fire resistance time by 5 minutes whereas cracks in disbonded material reduced the time by 15 to 17 minutes.

(c) 100% saturation and 50% saturation of sound material made no significant difference to the fire resistance. There were no signs of water saturation causing spalling.

(d) Disbondment with full or partial retention appeared to have little effect on the PFP performance if there were no openings to allow jet the jet fire to get between the material and the substrate. Disbondment with cracking, especially on an edge feature, leads to significant loss of fire resistance.

(e) If the material is fully bonded to a flat surface and there are no jet fire ingress points, lack of retention appears to have no effect. However, loss of retention from the bottom of a gouge has a slight effect and from a nick in an edge feature has a significant effect.

## SUMMARY

The largest temperature differences and consequent earliest times for water to be driven off all occur on a damaged web suggesting that damage to edge features is again most critical. The maximum substrate-heating rate after the water was driven off was 5.7°C $min^{-1}$. Although the test with water-saturated specimens had to be prematurely terminated, there was no evidence to suggest that these specimens would not have met their ratings. The only specimens not to meet their fire resistance specification were those with cracks.

 

**REPAIR TRIALS**

RESULTS

Figures 8, 9 and 10 show the specimen for trial 11 before and after testing. The purpose of this test was to determine the effect of chamferred and stepped repair joints.

Left Panel

The left panel incorporated a stepped repair joint. On this joint, fully expanded firm char was formed that was intact except for a crack near the edge of the panel on the left hand side where a small gap was visible where the Chartek had come away from Mandolite (see Figure 9).

Right Panel

The right panel incorporated a chamfered repair joint. At the interface between the Mandolite 550 and chamfered Chartek VII (see Figure 10), the Chartek had not come away from the Mandolite. However, there was a slight crack along the base of the Mandolite and along the Chartek. On the right side of the joint the char was more eroded and the mesh was exposed over a small area.

Web

The left hand side of the web incorporated a stepped repair joint. On the front of the left (stepped) side of the web, there was some damage to the Mandolite 550 and char had been eroded away near this zone.

**Figure 8.** Specimen for test 11 (before test)

**Figure 9.** Left panel after test (11)

**Figure 10.** Right panel after test (11)

 

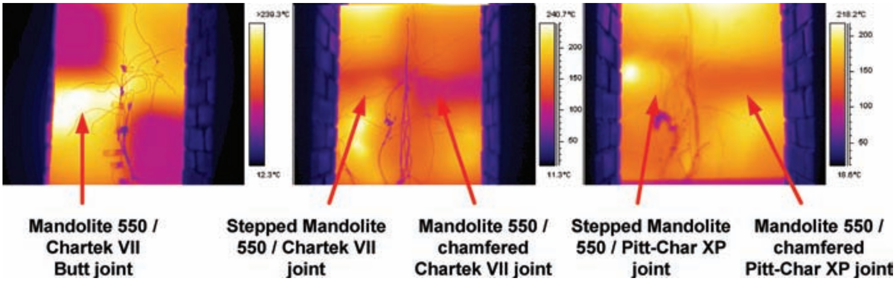


**Figure 11.** Thermal images (at 60 minutes) of repair joints

The right hand side of the web had a chamfered (Chartek VII) repair joint. After the test, the char on this side of the web was not firm and the mesh was exposed in the jet impact zone.

Overall, the temperature plots and thermal images indicated that, although both types of joint appeared acceptable, the chamfered joint performed better than the stepped joint. Thermal images comparing all three repairs are illustrated in Figure 11.

### CONCLUSIONS

The following conclusions were made in regard to the three types of repair assessed:

(a) Butt joints between sound cementitious material (34 mm thick) and new intumescent material (12 mm thick) are the weakest of the three types of joint assessed. When the jet impacts on the thinner coating of intumescent material, it is directed across the surface until it hits the edge formed by the thicker coating of cementitious material, where it is then directed away from the surface. The combination of high erosive forces and high heat flux appears to result in the char eroding away faster in this configuration.
(b) Stepping the sound cementitious material and overcoating this with new intumescent material gives an adequate join but there are still erosive effects and, because the thickness of intumescent material is not much greater than normal, the repair is not as good as chamfering the intumescent material.
(c) Chamfering the intumescent material with an extra loop of reinforcement appeared to be the best form of repair. It worked well with both a relatively hard intumescent material and with a relatively soft one. In addition, it worked as a repair on an edge feature.

## ACCEPTANCE CRITERIA FOR DAMAGED PFP

As reported by Thurlbeck (2006), current Offshore Safety Case submissions assume that PFP material is fit-for-purpose, performs as specified, and therefore performance standards

**Table 4.** Acceptance criteria for anomalies in epoxy intumescent PFP

| Anomaly | Criteria | Suggested action |
|---|---|---|
| Loss of topcoat | Loss of topcoat is **ACCEPTABLE**. | Action should comprise removal of loose topcoat material to a clean and sound material, a check that adequate thickness remains, and then re-topcoating with a recommended topcoat. A check should also be made to identify the presence of corrosion at the substrate surface. |
| Cracking | Fully bonded, fully or partially reinforced, material which contains cracks of less than 2 mm width is **ACCEPTABLE**. | The crack should be sealed and made watertight to prevent water ingress into the material which may leach out active agents associated with the intumescent process. |
| | Material which is disbonded or has damaged reinforcement, and has cracks of any width or depth is **UNACCEPTABLE**. | Action should comprise removal of the material down to the substrate, and back to soundly bonded material, and the implementation of the Manufacturers recommended repair. |
| Disbonded | Disbonded material of an area of less than 1 square metre, and which shows no signs of cracking or surface anomalies, is **ACCEPTABLE**. | No repair is necessary but the anomaly should be monitored. |
| | Disbonded material of an area of greater than 1 square metre, or a disbonded area of less than 1 square metre which has surface anomalies, is **UNACCEPTABLE**. | Repair should comprise removal of the material down to the substrate, and back to soundly bonded material, and the implementation of the Manufacturers recommended repair. |
| Loss/removal of material on structural steelwork | Loss of bonded, reinforced material over an area which is less than the acceptable area, and to any depth of remaining material which may include damage to the reinforcement, is **ACCEPTABLE**. | Action should comprise removal of any loose material and the application of an appropriate topcoat system. |

 

are met. Whilst this may be true, little or no information is available which provides an understanding of PFP performance in a damaged or repaired state. Verification of the performance standards could not, therefore, be reliably undertaken.

Required fire performance is generally specified in terms of time and temperature. In simple terms, the fire performance criteria specify survival times and are generally associated with ensuring an appropriate level of integrity is maintained to prevent an event from escalating, or for ensuring that personnel can be evacuated safely.

The fire performance requirements for a critical item should be detailed in the performance standards, along with the availability and reliability of the element, and the verification tasks to ensure that the performance is ensured.

The criteria are described by defining:

- Whether the protected item is a barrier or a loadbearing element;
- The type of fire/heat flux loading to which it is subjected;
- The critical temperature which should not be exceeded to ensure integrity and/or insulation requirements are met; and
- The time over which the temperature should remain below this critical temperature.

The data from the damage and repair trials described above, along with practical considerations, have been reviewed and a set of acceptance criteria produced, including a decision flowchart. This can be used by asset integrity personnel to assess the acceptability, or otherwise, of observed anomalies in PFP coatings and to determine whether the performance standard of a particular Safety Critical Element is maintained. Examples of the type of anomalies that (without corrective action) could be expected to lead to a failure (or reduced performance) include:

- Disbonded material of an area of greater than 1 $m^2$.
- Material which is disbonded or has damaged reinforcement, and has cracks of any width or depth.
- Loss of material, regardless of area, which is down to the substrate or has insufficient thickness to provide the required fire resistance performance.

Acceptance criteria for cementitious PFP and epoxy intumescent PFP material containing anomalies will be accessible, via the HSE website, in due course. An extract from the criteria, including suggested action where anomalies are observed, is shown in Table 4.

## REFERENCES

Health & Safety Executive, 1996, Offshore Technology Report OTI 95 634, Jet-fire resistance test of PFP materials.

ISO standard ISO/CD 22899-Parts 1 & 2, (draft).