4.1. Fire damaged structures

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4.1.1. INTRODUCTION

4.1.1.1. *General*

This chapter is concerned with technical aspects of appraisal of fire damaged steel, concrete and stone structures. The assessment of fire damages to structures follows a similar general process as appraisal of existing structures. It is possible to restore a fire damaged structure to its original load carrying capacity. In making a decision about repairing a fire damaged building, considerations should be given to aesthetic appearance, the reliability of repairs, the views of insurance company and the client, in addition to technical feasibility.

For member states of the European Union, safety requirements in case of fire are based on the Construction Products Directive (Council Directive 89/106/EEC: 21.12.1988). The Directive is applied to construction products as the essential requirement in respect of construction works. In Annex I of the Directive, the essential requirements for mechanical resistance and stability, and for fire safety, are summarised. The construction works must be designed and built in such a way that, in the event of an outbreak of fire:

- The load-bearing capacity of the construction can be assumed for a specific period of time;
- The generation and spread of fire and smoke within the works are limited;
- The spread of the fire to neighbouring construction works is limited;
- Occupants can leave the works or be rescued by other means;
- The safety of rescue teams is taken into consideration.

The load-bearing capacity of the construction may be modelled on the principles summarised in the parts of the structural Eurocodes which deal with fire.

Fire resistance is commonly used to characterize the performance of elements of structure in fire. It may be defined as the time for which elements of a structure satisfactorily perform their required functions under specified fire conditions. These functions may include the ability to avoid collapse, to limit the spread of fire and to support other elements. All construction materials progressively lose their ability to support a load when they are heated. If components of any structure are heated sufficiently they may collapse. The consequences of such a collapse vary, depending on how critical the component is in controlling the overall behaviour of the structure. In order to limit the threat posed by fire to people in a building, and to reduce the damage that a fire may inflict, large buildings may be divided into smaller fire compartments using fire-resisting walls and floors. Parts of a fire compartment may be further divided to protect the building from particular hazards within them. The performance of fire separating elements may rely on the ability of their supporting structure to continue to provide support under fire conditions. The criticality of an element is the degree to which its collapse would affect the performance of the structure as a whole. All of the main components of a structure are generally expected to exhibit fire resistance proportionate to the nature of the perceived risk. The nature of the risk is usually assessed on the basis of the size and proposed use of the building of which the structural element is a part; this is an important part of a fire safety risk analysis.

An amplified definition of the fire resistance of a structure or an element is its ability to retain, for a stated period of time, its load-bearing capacity, integrity and insulation, either separately or in combination. As a consequence of European harmonization, fire resistance is increasingly being expressed in terms of *R* (resistance to collapse, or the ability to maintain load-bearing capacity), *E* (resistance to fire penetration, or the ability to maintain the fire integrity of the element against the penetration of flames and hot gases) and *I* (resistance to the transfer of excessive heat, or the ability to provide insulation to limit excessive temperature rise.

Design for fire safety has traditionally followed prescriptive rules, but may now apply fire engineering or performance-based approaches, examples of which are given in documents EN 1990 (2002) and EN 1991-1-2 (2002). A fire engineering approach takes account of fire safety in its entirety, and usually provides a more flexible and economical solution than the prescriptive approaches. Within the framework of a fire engineering approach, designing a structure involves four stages:

1. Modelling the fire scenario to determine the heat released from the fire and the resulting atmospheric temperatures within the building.
2. Modelling the heat transfer between the atmosphere and the structure. This involves conduction, convection and radiation, which all contribute to the rise in temperature of the structural materials during the fire.
3. Evaluating the mechanical loading under fire conditions, which differs from the maximum mechanical loading for ambient-temperature design, due to reduced partial safety factors for mechanical loading in fire and changes in mechanical properties of the loadbearing materials.
4. Determination of the response of the structure at elevated temperature.

The design recommendations in codes contain simple checks which provide an economic and accessible procedure for the majority of buildings. For complex problems, considerable progress has been made in recent years in understanding how structures behave when heated in fires, and in developing mathematical techniques to model this behaviour, generally using the finite element method which may predict thermal and structural performance. In fire, the behaviour of a structure is more complex than at ambient temperature, because changes in the material properties and thermal movements cause the structural behaviour to become non-linear and inelastic.

4.1.1.2 Assessment

Assessment of a fire damaged structure differs from fire resistant design of the structure. In fire resistant design of a structure, the design fire is assumed; the material properties are those at high temperatures and the structure is assessed for reduced structural loads under the fire limit state. In assessment of a fire damaged structure, the engineer has to take into consideration the actual fire that has occurred in the structure; the material properties are those at ambient temperature but after being exposed to high temperatures; the repaired structure should be able to resist loads corresponding to the ultimate limit state, including the additional weight of any repair materials. In fire resistant design of a structure, the engineer obtains data by making suitable assumptions. In assessment of a fire damaged structure, the engineer obtains data by gathering evidences related to the specific damaged structure and the actual fire. It is important that the appraisal process starts as soon as the building can be safely entered and before the removal of debris to preserve vital evidence.

Reference Kirby et al (1986) provides guidance on reinstatement of fire damaged steel and iron framed structures. It gives detailed residual mechanical properties of different types of structural and reinforcing steels, iron and bolts after exposure to different high temperatures, metallurgical evaluation of fire damaged structural steelwork and a number of case studies. Figure 4.1.1 is a flow chart for reinstatement of fire damaged steel structures.

Reference Concrete Society (1990) provides detailed guidance on assessment of fire damaged concrete structures and design for repair. Detailed information of the effects of high temperatures on structural materials is provided. Different popular methods of assessing fire damaged concrete are described. Detailed guidance is given on how to design and specify repair methods to restore the load carrying capacity of the fire damaged building. A number of detailed examples are included to demonstrate application of the procedures in this document. Figure 4.1.2 is a flow chart for assessment and repair of concrete structures.

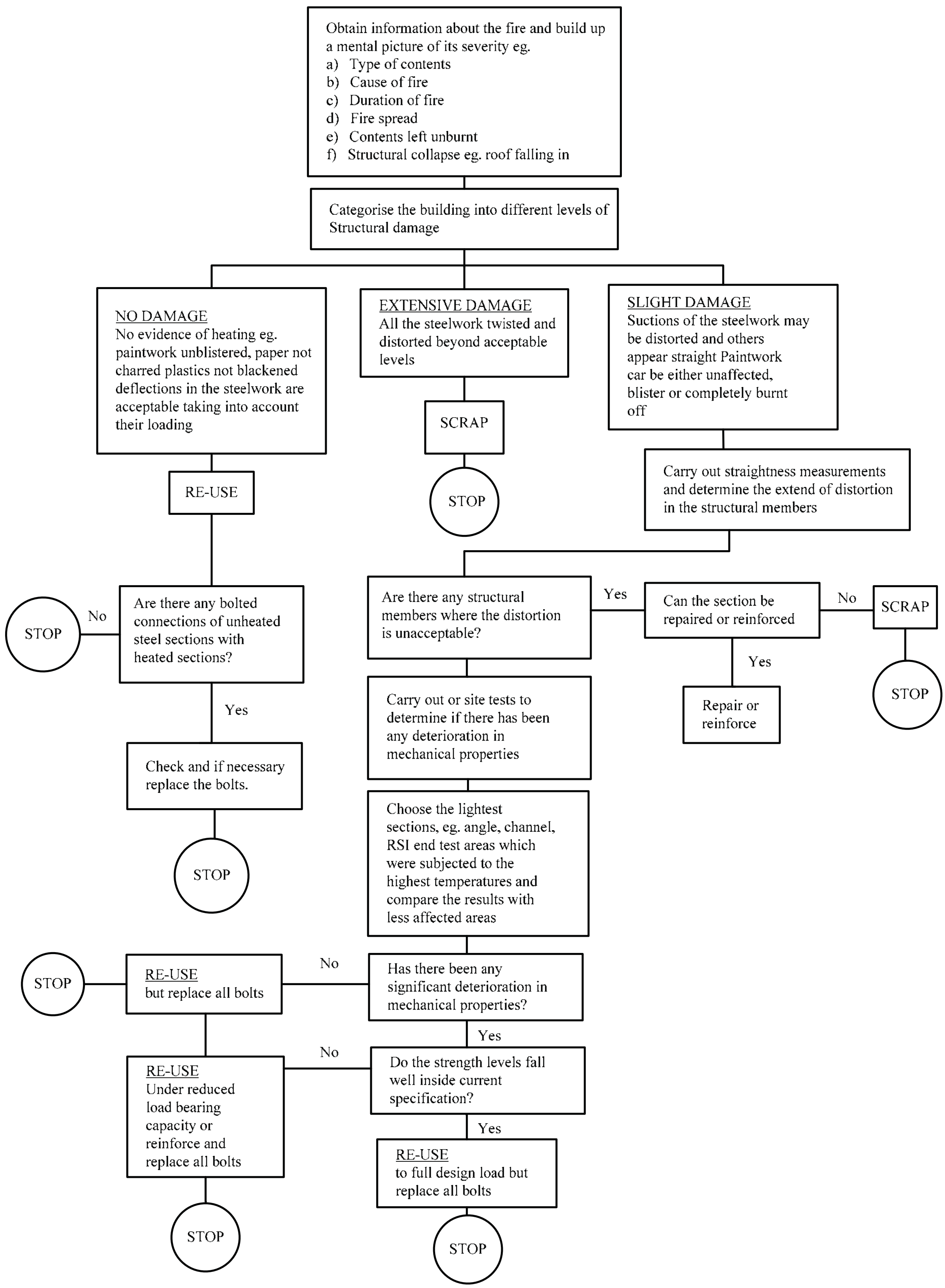

Figure 4.1.1. Appraisal procedure for fire damaged steel structures, see (Kirby et al 1986).

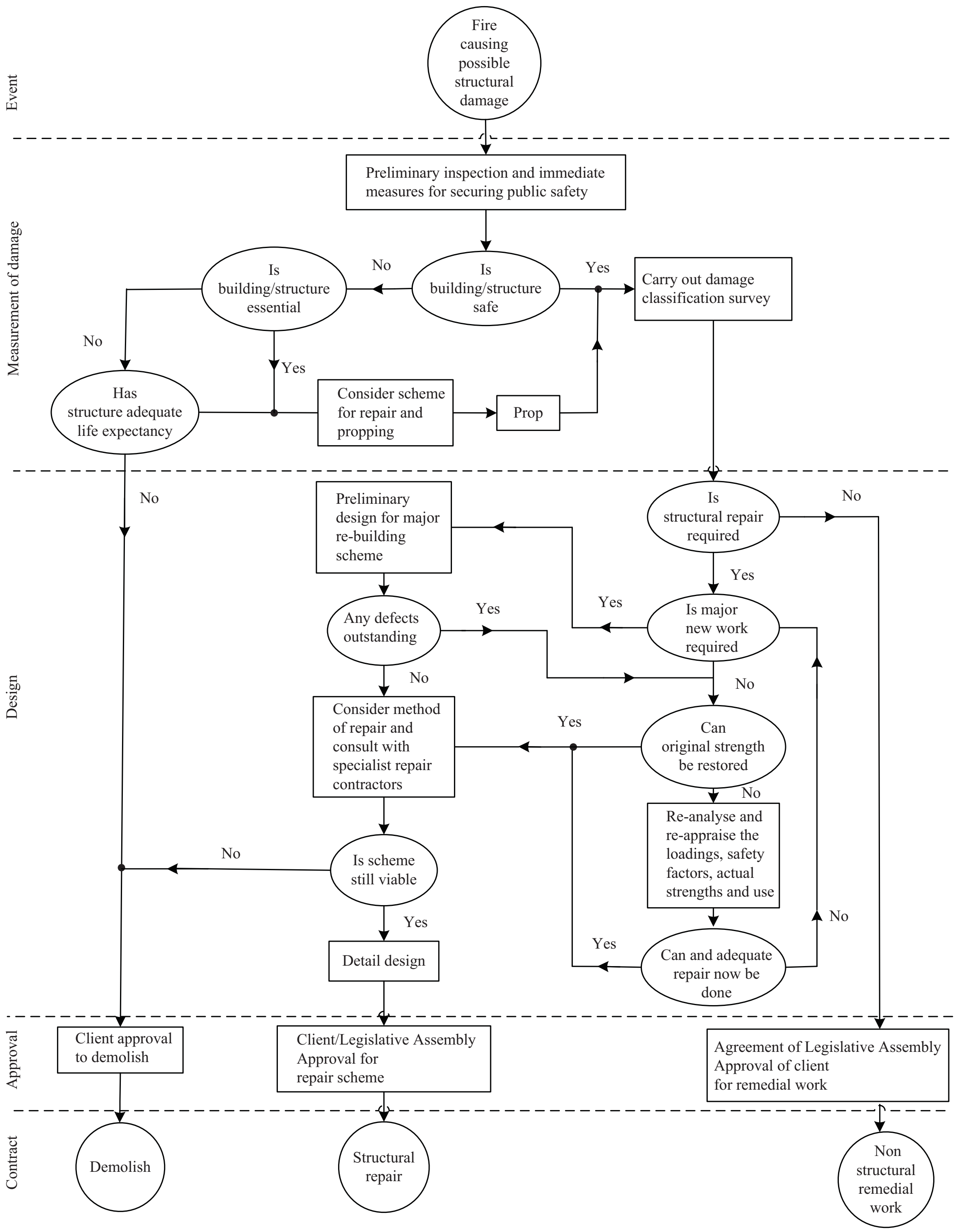

Figure 4.1.2. Appraisal procedure for fire damaged concrete structures, see (Concrete Society 1990).

An important aspect of assessing fire damaged structure is to obtain mechanical properties of the structural materials using suitable non-destructive testing methods. Reference CIRIA (1986) provides more detailed explanation of different methods of assessing concrete, some of which are referred to in Reference Concrete Society (1990). This reference is for general use of assessing concrete, but many of the test methods are applicable to fire damaged concrete.

Reference ISE (1996) is a general document for appraisal of existing structures, the general procedure of which may be followed in assessment of fire damaged structures. It also provides information on temperature effects on a selection of non-structural materials, which may be used to establish the history of the fire.

Reference SCIF (1991) provides a detailed case study of assessment of fire damage to the Broadgate building (a steel framed composite structure) in London, which was extensively damaged by a severe fire during its construction before fire protection to the steelwork was installed. The fire damaged structure was successfully reinstated by replacing the fire damaged floors and columns. The cost of replacing the fire damaged structure was a relatively small fraction (<10%) of the total repair bill, most of which was spent on cleaning the building.

Stones are used in many recent and heritage buildings. A study of sandstones at elevated temperatures shows that heating affects the internal structure and mineral composition of natural stones, through influencing the petrophysical parameters (porosity, strength, water adsorption, colour) of the stones. These changes are not always adverse. Hajpál & Török (2004) and Török et al (2005) describe how the mineralogical composition and texture of natural stones influence their resistance to fire and thermal characteristics. The heat resistance of different quartz sandstones depends on the type of the cementing mineral, the amount of cement (grain/cement ratio), the grain size (fine, medium, coarse) and the grain to grain or matrix to grain contacts. Compact stones show more dramatic change in porosity at elevated temperatures than the less cemented ones. A porous and cement rich stone is more adaptable, being able to accommodate thermal expansion induced additional stresses. Silica cemented, ferruginous or clayey stones are less sensitive than the carbonatic ones, which disintegrate at higher temperatures.

4.1.2 DESIGN PROCEDURE

The general procedure of appraisal of a fire damaged structure comprises of the following steps: initial site visit, desk study, detailed collection of evidence, damage assessment and specification of repairs. The purpose of the site visit is to gain an early indication of the scale of damage to the structure and to advise on safety of the building and to recommend measures to protect the general public and other essential personnel.

The purpose of the desk study is to collect relevant information (e.g. original design of the building, construction materials, usage before fire, cause of fire, duration of fire, fire spread, contents left unburnt) by examination of physical evidence, interview of the fire brigade and witness. Using the preliminary data gathered, the engineer should establish a strategy for more detailed assessment and data gathering.

Fire damages to a structure can be broadly grouped into four categories: no damage/superficial damage, total damage, major damage and reparable damage. No/superficial damage requires no structural repair; total damage leads to scraping of the total structure; major damage requires replacement of the damaged structural members. For these categories, decisions can be made quickly without the need to undertake detailed assessment. Reparable damages are those that may be repaired but there is a high degree of uncertainty about the residual load carrying capacity of the structure. The main objective of damage assessment is to decide with as much confidence as possible the residual mechanical properties of the fire damaged materials so that the fire damaged structure can be restored to its required load carrying capacity.

4.1.3 STRUCTURAL ASPECTS

The residual mechanical properties of fire damaged materials may be obtained using the following methods: (1) by direct measurement using Non-Destructive Testing (NDT) and destructive testing; destructive testing should be kept to minimum and should only be used when there is low confidence in NDT results; (2) by direct assessment of maximum material temperatures and links to material residual mechanical properties – temperature relationships; (3) by establishing the fire history, from which the material temperature history may be established using heat transfer; afterwards, using the residual mechanical properties – temperature relationships. Due to uncertainty in results obtained from these different methods, it is important to correlate the different results to improve confidence in them. It is also important to make conservative (safe) assumptions when evaluating residual load carrying capacities of fire damaged structures; for example, assuming simple supports and ignoring any beneficial effects of the restraints.

The documents (Kirby et al 1988, Concrete Society 1990, ISE 1996) described in the Guidelines section of this technical sheet may be consulted to obtain residual mechanical properties – temperature relationships for steel and concrete. Additional data may be obtained from Outinen and Mäkeläinen (2004), see e.g. Figure 4.1.3; Pang (2006), and Chan (2009) for steel, from Dias (1992) for concrete and from Yan and Wong (2007) for high strength concrete; and from Hajpál and Török (2004), Hajpál (2008) and Török and Hajpál (2005) for sandstones. Materials expand at high temperatures, which may cause brittle materials remote from the fire site to suffer damage. It is important to assess the entire structure for fire damage. For example, expansion of floors directly involved in a fire may damage the walls in remote places from the fire.

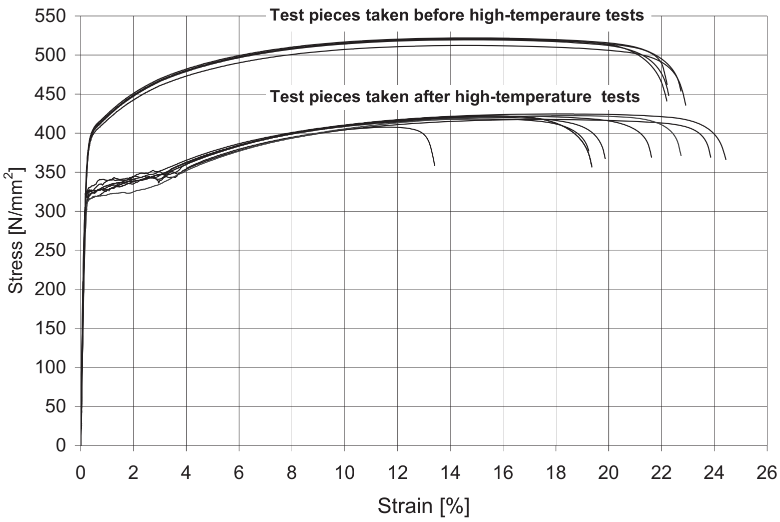

Figure 4.1.3. Tensile test results for structural steel S350GD+Z, the test pieces taken before and after high-temperature compression tests, where the material reached temperatures up to 950°C, see Outinen, Mäkeläinen, 2004.

NDT methods for fire damaged steel include Hardness test and metallurgical microscope. Hardness test is simple and easy, but the hardness test results should not be used to guarantee the material to an appropriate specification, for which coupon tests are required. Microscopic test requires specialist personnel and equipment. It is used only when it is essential, e.g. to provide information on the micro-structure of metal so as to establish an accurate picture of the heating environment.

Methods of assessing fire damage to concrete include colour observation (e.g. pink indicating about 300°C), visual classification, NDT testing (Schmidt hammer, ultrasonic pulse velocity, thermoluminescence) and destructive testing (cores). It is important to choose the appropriate testing method before detailed assessment starts. The Schmidt hammer test is a simple and cheap approach, but it only gives an indication of the concrete properties near the surface of the structural element and its results may contain large scatters; the ultrasonic pulse velocity method is also easy to use and may be used to detect internal cracks of concrete, but it requires access from both sides of the structure; the thermoluminescence method involves taking a small amount of concrete through a considerable depth; through analysis of the thermoluminescence lost due to heating, the temperature profile through the concrete depth may be established, from which the mechanical properties of concrete may be obtained.

Being a material that is made at high temperatures, mild steel recovers much of its initial strength and stiffness after fire exposure. Therefore, a fire damaged steel structure can normally be reinstated. Unless severely distorted to affect appearance, steel structural members can normally be retained. High strength bolts are made by quenching. Exposure to high temperatures above 500°C has the similar effect as tempering, which would reduce the residual strength of bolts. Generally, bolts after exposure to high temperatures should be replaced. If the reinstated steel structure requires fire protection, it is important that smoke deposits on the steel surface are removed before application of fire protection materials.

Various methods may be employed to repair fire damaged concrete structures, including reconstruction (major repair after extensive damage or sprayed concrete is difficult), sprayed concrete, resin repairs (for repairs to lightly spalled areas), overcladding (non-structural materials such as plasterboard, to restore appearance/restore fire resistance/durability), provision of alternative supports.

4.1.4 CASE STUDY OF A STEEL COAL FEEDING BRIDGE

4.1.4.1 Fire damaged structure

In September 2005, fire occurred on the coal feeding bridge in the Opatovice power station, Czech Republic, when unloading of a wagon hit the transport corridor, see Vácha (2006) and Figures 4.1.4 to 4.1.6. About 100 m of the concrete corridors and 120 m of the steel transport bridges (four truss bridges of span 30 m each) were affected, Coal transport infrastructure was completely burned and the bearing structure was noticeably damaged. The power station depends on coal supply so it was important that the supporting structure was reconstructed to be functional as soon as possible. The steel structure was noticeably affected by the high temperature, which was estimated to be about 1000°C, based on its colour during the fire.

The four steel coal bridges were similar. There were 30m span trusses with upper and lower stiffening trusses. One bridge was inclined. The lateral stability of the bridge trusses was achieved by massive rigid frames spaced at 3 m. All the connections were riveted. The fire damaged all sheathing of the walls and roof. The upper part of the bridge suffered local deformations of the upper crossbeam, the truss stiffeners and the end frames, with the maximum deformations around 100 mm. The upper parts of the main trusses were deformed only at a few locations. The lower parts of the structure would not have suffered any structural damage during the fire because the surface painting still remained after the fire. As shown in Figure 4.1.4, he inclined bridge was the most damaged. The total deflection of the unloaded structure reached from L/600 to L/500.

Figure 4.1.4. The coal bridge after the fire.

Figure 4.1.5. Deformed upper stiffening truss.

Figure 4.1.6. Deformed purlins.

4.1.4.2 Reconstruction

Instead of replacing all the fire damaged bridges, reconstruction of only parts of the structure was undertaken to minimise the plant down time. The reconstruction started through detailed diagnoses in the following steps:

- Mechanical property tests were performed on selected specimens by standard coupon tests. The results of extended measurements of steel heated to 950°C are summarised in Table 1. The steel grade used was S235. It had good weldability before and after the fire and the fire incurred only negligible damage to the yield stress of the steel. In only one place outside the main bridge was steel found to be brittle due to fire attack.
- The change in microstructure of steel due to heating and cooling was visible on all 54 observed specimens. However, these changes may be accepted because of the slight changes in mechanical properties of the steel.
- Visual checks of the geometry of the structure and its elements were followed by detailed measurement of all major positions of the structure, including joints of the trusses and the rail of the conveyor.
- Straightness of all compressed elements of the main trusses was checked by geometric measurements.
- Chemical analyses were performed to determine contamination of the surfaces so as to prepare cleaning and the following-on corrosion protection.

Table 4.1.1. Measured yield stress and strength of steel with and without temperature effect, MPa.

	Yield stress				Strength			
Thickness, mm	10	20	30	6	10	20	30	6
Steel grade	S235	S275	S275	S355	S235	S275	S275	S355
Affected	226	297	307	309	439	497	471	465
Unaffected	269	352	333	374	462	514	481	535
Reduction, %	16	16	8	17	5	3	2	11

The major aim for the design and implementation strategy of the reconstruction work was to minimise the reconstruction time. The current stage of the structure was analysed based on the material properties obtained above. The following decisions were taken:

- All elements with excessive deformations were replaced; the maximum allowed out of straightness was 10 mm;
- When performing structural analysis, the mechanical properties of all steel elements attacked by fire were reduced by 10 %;
- For the riveted connections affected by fire, but not visibly deformed, the resistance was reduced by 15 %;
- Second order analyses were adopted and they incorporated the effects of the allowed maximum deformation of 10 mm;
- The upper truss stiffeners and the upper crossbeams were changed, see Figure 4.1.7;
- The upper parts of the props of the end stiffeners were changed as well;
- One deformed diagonal member in the lower stiffening truss was changed at each horizontal bridge, see Figure 4.1.8;
- For the inclined bridge, all the lower cross beams and lower stiffening trusses were replaced;
- Based on detailed calculation, a few riveted connections were strengthened by welding on site;
- After the reconstruction, the structure was loaded by an operational test, which proved that the structure recovered its full static behaviour, see Figures 4.1.9 and 4.1.10.

Figure 4.1.7. Replacing of the end frame.

Figure 4.1.8. View into the reconstructed bridge.

Figure 4.1.9. The uncovered bridge during its reconstruction.

Figure 4.1.10. The reconstructed bridge during proof of behaviour by loading test.

4.1.5 FURTHER DEVELOPMENT

Assessment of a fire damaged structure differs from fire resistant design of the structure. In assessment of a fire damaged structure, consideration is taken into the actual fire that has occurred in the structure; the material properties are those at ambient temperature after being exposed to high temperatures; the repaired structure should be able to resist loads corresponding to the ultimate limit state, including the additional weight of any repair materials.

Since a real fire will generate highly non-uniform temperature distribution, the residual mechanical properties of the fire exposed materials may be significantly different in different locations of the structure. Furthermore, it will not be possible to obtain detailed information of mechanical properties of materials through definitive destructive testing. Therefore, in assessing a fire damaged structure, to achieve confidence in material properties, the engineer should correlate data from a variety of sources, including mechanical properties from non-destructive and destructive (to be used with care) tests, temperature history of the fire and temperature history of the materials. The engineer should also take into consideration structures unexposed to the fire but may be severely affected by the fire through thermal deformation.

Frequently, fire damaged structures can be successfully repaired to fulfil their original functions. A number of significant references are available to guide the engineer in this process.

ACKNOWLEDGEMENTS

The fire engineering work of this study and outcome has been achieved with the financial support of the Ministry of Education, Youth and Sports, project no. 1M0579.

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