EXPERIMENTAL DATA RELATING TO THE PERFORMANCE OF STEEL COMPONENTS AT ELEVATED TEMPERATURES

Prepared by The Steel Construction Institute for the Health and Safety Executive
EXPERIMENTAL DATA
RELATING TO THE
PERFORMANCE OF STEEL
COMPONENTS AT ELEVATED
TEMPERATURES

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FOREWORD

This report is one of twenty six work package reports written as part of the Joint Industry Project on Blast and Fire Engineering for Topside Structures. The Project Phase 1 started in May 1990 to collate, appraise and disseminate information on blast and fire loads, and on the resistance of structures and facilities to these loads. The titles and numbers of the reports generated by this project are as follows.

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The purpose of these reports is to collate, review and critically appraise the current state of knowledge in each of the listed subject areas. They discuss the current state of technology as applicable to each of these areas. They also indicate the areas of significant residual uncertainty. The objectives and scope of each report are outlined in the ‘Work Package Descriptions’ included in each report.

The reports are written for use by engineers with specialist responsibilities for specific tasks associated with safety against potential fires and explosions in the design of Topsides on Offshore Structures (eg as part of a Formal safety Assessment) or for the use by their expert advisors. They are intended to be both expert and authoritative.

These reports have also been used as the basis for establishing interim guidance and to identify any necessary further research or development work. These are also project deliverables and are issued as separate documents.

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EXECUTIVE SUMMARY

In this Work Package an examination of the temperature dependent material properties for the various types of steels that are commonly found in offshore installations has been made.

Two broad groupings of steel material types are identified. These are the structural steels (low carbon steels which belong to material standards BS 4360, BS 7191 and API Grade 5L) and 'boiler' steels used for pressure vessels and some piping. Within these two broad groupings the underlying behaviour of steel at elevated temperature is largely defined by the chemical composition but this may be modified by the manufacturing process.

For design purposes the elevated temperature properties are divided into two groups, the mechanical properties such as yield strength and the thermal properties such as the specific heat of the material.

The range of temperatures for which material properties are required is itself a function of material type, but would normally include any temperature at which a material retained between 5 and 10 percent of its yield strength at 20°C. For most fire analysis purposes, material and thermal properties to temperatures of 750°C should be determined.

The type of treatments that a steel has been subjected to during the steel production process governs the strength and behaviour of that steel at elevated temperatures. Such treatments include normalising, quenching, tempering and stress relieving. If strength has been increased by heat treatment then it may be lost in the uncontrolled heating by a fire.

There is limited test data at elevated temperatures for steels which are not the common structural steels. The test data which are available should be used with caution and the user is advised to consider the experimental basis of any data.

Steels with enhanced properties at elevated temperatures ('fire-resistant' steels) are presently available, these steels being more expensive than common structural steel and yet cheaper than the austenitic grades of stainless steel. Care should be taken when comparing different steels since the properties reported may, for example, be a 'lower bound' value for one steel compared with an 'average' value for another. Generally speaking for temperatures in the range 300°C to 500°C, 'fire-resistant' steels maintain better strength characteristics than low carbon structural steels.

Stainless steels have generally better fire resistance qualities than carbon steels in the temperature range 550°C-900°C. However, each type of stainless steel should be reviewed in its own right. This is particularly so if a stainless steel is to be considered for structural use.
Presently stainless steels are mainly used for pressure vessels and pipework, and the properties given relate to these uses. In an offshore structural environment, stainless steel has been used for cladding requirements and in heat shields.

Consideration should be given to the limited use of high strength RQT (Roller Quenched and Tempered) steel in offshore structures. Although high strength and low temperature toughness is inherent in this type of steel, enhanced properties are also found at high temperatures (to 650°C). However those data available are minimal, product specific and incomplete for fire-resistance considerations. Further testing and properties analysis may therefore be required.
1. **INTRODUCTION**

The study area of Fire-Resistance in this Project is divided into seven subject areas, namely:

- **Work Package FR1:** Experimental data relating to the performance of steel components at elevated temperatures.
- **Work Package FR2:** Methodologies and available tools for the design/analysis of steel components at elevated temperatures.
- **Work Package FR3:** Passive Fire Protection - performance requirements and test methods.
- **Work Package FR4:** Availability and properties of passive and active fire protection systems.
- **Work Package FR5:** Existing fire design criteria for secondary, support and system steelwork.
- **Work Package FR6:** Fire performance of explosion-damaged structural and containment steelwork.
- **Work Package FR7:** Thermal response of vessels and pipework exposed to fire.

A detailed description of Work Package FR1 is given in Appendix C.

This Work Package examines the data relating to the performance of steel components at elevated temperatures. The aim is to produce a summary of available knowledge and to provide practicing engineers who design steel fabricated structures with a reliable data source.

This document highlights the complexities relating to varieties of steel, type of testing, and rate of heating associated with the measurement of material properties at elevated temperatures. Although the designer primarily requires the stress-strain properties of structural grades of carbon steel at elevated temperatures, an appreciation of these complexities has to be considered.

For commonly used structural steels, the relationship between steel temperature (not fire temperature) and its mechanical properties are given in Table 1.1.

For definition of terms in this report refer to the Glossary in Appendix A.

1.1 **Objectives**

The stated objective of this Work Package is 'To identify what available knowledge can be used by the offshore industry in the assessment of the performance of steel components at elevated temperatures and to identify gaps in present knowledge'.
There is a need to know the properties of steel at elevated temperatures in order to design structures to resist fires.

The data review has concentrated on collecting available information defining stress-strain curves at elevated temperatures for steels commonly used offshore. Also the test methods applied to obtain these stress-strain curves have been analysed. Data relating to other physical properties such as thermal expansion, thermal conductivity and specific heat have also been collected. These physical properties are referred to as the ‘thermal properties’ of steel throughout the report.

1.2 Background

Traditionally steel design engineers have taken the simplistic view that steel material properties change with temperature such that collapse of a structure occurs at 550°C. In this simplistic approach no effect of in situ load carried at the time of heating was considered. This approach is still used for onshore structures, although in Europe it is about to change with the introduction of codes of practice for fire-resistant design of structures. In the UK, BS 5950: Part 8 [1] was published in July 1990 and the draft Eurocode EC3: Part 10 [2] and the draft Eurocode EC4: Part 10 [3] were published in April 1990. These codes contain elevated temperature properties for the commonly used structural steels.

Although the data from onshore codes which relates steel performance to temperature in a fire can be relevant to offshore design work, fire load characteristics for an offshore structure fire design should be chosen based on its applicability in that situation. Further information on fire load characteristics for offshore fires can be obtained in report on Work Package FL2.

For offshore structures there has been a sparsity of data relating to the fire endurance of steel structural elements, as the offshore design codes have tended to emphasise (1) Firewalls and (2) Active systems.

In 1983 the Burks, Green and Partners report [4] stated how the onshore methods of column testing would give misleading results because of the effects of restraint. The report also pointed to the error of using 'cellulosic' data for offshore fires, and this primary objection remains valid.

1.3 Required Steel Properties

In assessing the performance of steel structures in a fire, a number of properties are required. In offshore structures many steel types are used, as explained in Section 2. Many of these properties are readily available for the grades of steel likely to be used in offshore situations; however the data can be incomplete. Also data published may be in a form which is not suitable for use in analysis.
The following properties would normally be sufficient for a thermal and structural analysis.

Thermal properties:

- Specific heat
- Thermal conductivity
- Coefficient of expansion
- Emissivity
- Absorptivity

Mechanical properties:

- Young's modulus
- Stress-strain curves

In Section 3, the properties for steels at elevated temperatures are given for common and special steels. Mechanical and thermal properties vary with temperature, but the variation may not always be a smooth curve. For example, due to a phase change, the common structural steels actually shrink slightly at about 700°C (see Figure 3.6). This may cause increased stress in fully restrained structures. Generally it is possible to carry out an analysis using constant (average) values, but where possible the variation due to temperature should be taken into account.

1.4 Effect of Steelmaking Process

For design at normal temperatures, the method by which the steel has obtained its properties is not generally important. However, the 'room temperature' properties are very dependent on the process route by which the steel was produced. The steelmaker can improve the strength of steels by controlling the rate of cooling of the steel and by rolling the steel at different temperatures. An example of this is a quenched and tempered steel in which rapid cooling is linked to controlled rolling.

Microstructure

'Steel' may have a face-centred cubic atom arrangement (austenitic) or a body-centred cubic atom arrangement (ferritic). In broad terms, steels with a face-centred cubic atom arrangement will tend to have enhanced high temperature properties, for example, austenitic stainless steels and 'fire-resistant' steels.
Some of the more common treatments are described below:

1.4.1 Normalising

This involves heating the steel to a temperature above the critical temperature for the transformation of austenitic to ferritic steel and then cooling, often in still air. The critical temperature is about 720°C. Normalising refines the grain size and provides improved uniformity of structure and properties.

1.4.2 Quenching

This involves heating to above the critical temperature followed by rapid cooling, often with water. Quenching will make the steel brittle, but will increase strength and hardness. It is normal to temper steels following quenching. If the properties of the steel are improved by tempering, then the enhanced strength will be lost after heating above 650°C in a fire.

1.4.3 Tempering

This involves heating to a temperature below critical followed by controlled cooling. Selection of the temperature and cooling will give the desired mechanical properties.
It is important to note that the greater the temperature and longer the exposure that a quenched and tempered steel is put through during a fire, the greater is the degradation in the mechanical properties of the steel at normal temperature. This could be critical for a structural member which has been exposed to a fire, or some other form of significant temperature increase, and yet is still in service.

1.4.4 Stress Relieving

This involves heating to a sub-critical temperature to release stresses caused by cold working or fabrication. It is not intended to significantly modify the properties.

1.5 Chemical Composition

The properties of steel are clearly dependent on the chemical composition. For most structural steels the chemical composition is designed to give the required properties at normal temperatures but when considered at high temperatures, such as in a fire, there is a possibility that something in the composition which improves properties at normal temperature may have a negative effect on the properties at high temperatures. For steels designed to be used at high temperature it may not be possible to obtain high strength at low temperature. For these steels the proportionate loss in strength at high temperature is lower than for the commonly used structural steels. The elements which have the most effect on properties are:

1.5.1 Carbon and Manganese

Both these elements have similar effects on the properties of steel, but to different extents. Increasing them causes an increase in hardness and strength, together with a decrease in ductility and weldability. They have little effect on the elevated temperature properties.

1.5.2 Chromium

Chromium increases the corrosion resistance and the high temperature strength. It is most effective when used with molybdenum.

1.5.3 Molybdenum

Molybdenum increases the high temperature strength and increases creep resistance. It is normally used with chromium.
1.5.4 Titanium

Titanium is a deoxidizer. It is also useful in restricting the effects of nitrogen and carbon since it readily combines with these elements. Titanium will lessen grain growth and may be used to prevent steel from hardening. It is also used to stabilize austenitic stainless steels.

1.5.5 Vanadium

Vanadium tends to produce a fine grain structure during the heat-treating process. Because of this, vanadium often eliminates the bad effects of overheating. It also tends to promote hardenability; it causes a marked secondary hardness that resists tempering.

1.6 Miscellaneous Effects of Temperatures

Section 1.4 discussed the effect of the steelmaking process on steel properties. This section is concerned with the effect of high temperatures on finished steel, e.g., during a fire.

1.6.1 Oxidation

Above about 400°C the rate of oxide formation on an exposed steel surface increases. This may become significant during a prolonged high temperature fire. However, relative to the loss of strength of the base steel, the loss in material thickness will be negligible.

Oxidation may indirectly affect the optical properties of the steel surface (emissivity and absorptivity). These are used by fire loading models to determine the heat flux being received by the steel. No data was found specifically addressing this issue.

1.6.2 Oxygen Starvation

In certain environments, and particularly where oxygen is absent, there are a number of corrosion mechanisms which attack steel. Most of these mechanisms are accelerated at high temperatures. These mechanisms shall not be considered further since, like oxidation, they affect only the steel surface. They may also affect optical properties, but again the effects are unknown.
1.7  
Roller Quenched and Tempered Steel (RQT)

RQT steels are produced by heating steel plates into the austenitic range, about 900°C, followed by high pressure water quenching. The plate is then tempered at carefully controlled conditions of temperature and time, to give an optimum combination of strength and toughness. RQT steels have high strength and toughness compared with normalised steels.

1.7.1  
Types of RQT Steel

RQT steels are generally produced to have a greater strength than the common structural steels. Commonly RQT steels are available in strengths from 450 N/mm² to 700 N/mm². They are produced in plate, bar or hollow section form. Sections are not normally produced from RQT steel.

RQT steels are very often "proprietary" steels and are not made to national or international standards. Exceptions to this rule are BS4360 Grade 55F and 55EE.

1.8  
Stainless Steel

All stainless steels exhibit good corrosion resistance at low and elevated temperatures, but the austenitic grades have a face-centred cube microstructure which gives them enhanced performance at elevated temperatures.

It is generally true that a stainless steel alloy has better fire resistance qualities than a carbon steel alloy for temperatures in the range 550°C to 900°C (see Figure 3.11).

The sources of high temperature data for stainless steels do not always quote the heating rates or the type of testing undertaken, for example the INCO data [5]. Such data should be used with caution.

1.8.1  
Types of Stainless Steel

In general stainless steels can be divided into three categories which are as follows:

1)  
the martensitic group, often termed plain chromium types of stainless steels, which contains approximately 13% chromium and, with the odd exception, have no other major alloying element. These steels can be hardened by heat treatment.

2)  
the ferritic group contains approximately 17 to 30% chromium, again with no other major alloying element, but cannot be hardened by heat treatment.
3) The austenitic group contains approximately 18% chromium and 8% nickel. They cannot be hardened by heat treatment, but harden rapidly when cold-worked. Additions of molybdenum are made to certain grades to increase their corrosion resistance, whilst others have titanium or niobium added to stabilize the carbon. An alternative method of obtaining a completely stable steel is to control the carbon level at 0.03% maximum.

**Alloy Variations**

There are a very large number of possible 'stainless steel' alloys and a number of these can be used in offshore platforms.

The martensitic stainless steels contain about 16% chromium with about 2% nickel and small additions including molybdenum, vanadium, tungsten, copper and boron. Such steels have been used for blades for steel turbines, high-strength rivets and bolts, and other applications requiring great strength at moderately high temperatures.

Another group of stainless steel alloys are known as the semi-austenitic precipitation-hardenable steels. These contain 17% chromium, 7% nickel, about 0.15% carbon, and other elements including molybdenum and aluminium. They may be regarded as derivatives of the austenitic group of stainless steels previously mentioned. These steels derive their group-name from the fact that they can be heat-treated to high strength by a special process known as precipitation hardening. These stainless steel alloys are used extensively in aircraft, and for other high specification requirements.

A further group, known as the cold-rolled austenitic stainless steels, contain chromium, with either or both nickel and manganese and a small amount of nitrogen. They can only be hardened by cold working. Although they can be used for only short periods of time at temperatures over 400°C they have the advantage that very high strengths can be developed by cold-rolling, without a subsequent heat-treatment process being necessary.

### 1.9 Steels with Enhanced Properties at Elevated Temperatures ('Fire-Resistant' Steels)

It is possible by slightly altering the chemical composition and rolling process to modify a conventional structural steel to give enhanced properties at elevated temperature. Such steels are produced by the Nippon Steel Corporation and also by British Steel.

At the time of writing only limited information is available, but it would seem that the 'fire-resistant' steels maintain their strength significantly better than the normal structural steels, as shown in Figure 3.16.
2. THE USE OF STEEL OFFSHORE

2.1 Primary Structure

In examining the properties of steel at elevated temperatures, it is vital to know which steels are used in offshore platforms and where they are to be found. As far as fire resistance is concerned, the conditions to which the steels are subjected under normal service requirements are also of importance. Consideration should also be given to steels whose material properties have been revised during the life of a platform. This is important in the re-analysis of offshore platforms where the appropriate material properties have to be used.

Offshore platforms are constructed using numerous types of steels; these steels being specified with often diverse material standards depending on the function of the components. There has been a tendency to use a mixture of British and American standards for structural steels, depending on whether plate or tubular sections are considered. To avoid the use of a mixture of different types of structural steels, a common standard has recently been introduced. This is the publication of the Engineering Equipment and Material Users Association document "Steel Specification for Fixed Offshore Structures", 1987, generally known as "EEMUA" [6].

However, for steel structures designed before EEMUA and for topsides equipment, pipework, pipelines and risers (these are not included in EEMUA), the diversity of standards remains a stumbling block in describing the material properties for a wide range of supporting and utility structures. The following section therefore attempts to describe the most important material types which can be bracketed within the term 'steel' and where they are to be found on topsides and the supporting structure.

2.1.1 Substructures

The substructures fall into a number of categories. Steel structures include barges-launched jackets, self-floating towers, tension leg structures, and semi-submersible vessels. Concrete platforms tend to be all of a similar design, being vertically transported self-floating towers with gravity foundations. Other hybrid or sub-groupings can be recognised such as the steel gravity platform and the crane installed jacket.

Steel types found in the substructure fall into two broad divisions, fabrication steel and reinforcing steel, the latter being found exclusively in concrete towers. This document however deals exclusively with steels use for steelwork fabrication only.

Fabrication steels used in offshore platforms are summarised in Table 2.1.
BS 4360 Grade 50 [7] type steels and BS 7191 [8] Grade 355 (EEMUA 355 [6]) type steels are the most predominant steels to be considered. They are used as plate sections for rolling into tubulars of diameters 650mm to 11000mm and above. These steels are also used for braces, stiffened leg sections and for node barrels both stiffened and unstiffened. Within this Grade 50 division there are a number of sub-grades.

Recently BS 4360 Grade 55 type steels have been used in a limited number of platform designs.

API specification 2H [9] gives a material description which is broadly similar to BS 4360 and uses similar grade descriptions.

API tubular pipes Grades 5L [10] are used in seamless steel tubulars of diameter 450 mm and below. API Grade 5L B steel has a yield strength of 241 N/mm² and API 5L Grade X52 has a yield of 358 N/mm². EEMUA [6] gives API 5L X42 type steel as equivalent to EEMUA 275D and API Grade 5L X52 equal to EEMUA 355D.

Cast steel of equivalent strength to BS 4360 Grade 50 steel is used in nodes and in lifting attachments. The supply of cast nodes is under agreement with specific suppliers and the detailed material specifications vary with each particular contract.

API Grades 5L [10] are used in seamed tubulars in the range 450mm to 700mm diameter, and also for risers and J-tubes.

BS 4360 Grade 43C steels are used in a number of applications, mainly for secondary steelwork details such as boat landings, walkways and ladders.

In some older platform designs (particularly gas platforms) the tubular bracings have been fabricated from BS 4360 Grade 43C or similar material.

Grade 50D and Grade 43C steels are used as welded plate sections in the conductor ladder bracings.

The dominant steel type to be found in substructures is BS 4360 Grade 50D, which accounts for the largest tonnage in conventional steel platform designs. On earlier projects the steel type was often specified as type I or type II, the designation being used to differentiate between through-thickness guaranteed (Suffix "Z" steel in BS 7191 and EEMUA) material and non-through thickness guaranteed material. BS 7191 and EEMUA Suffix "Z" material is now specified for the fabrication of nodal steels in jackets, which overcomes the previous difficulties of type I and type II classification.

The dominant fabrication method for jacket structures is to connect bracings and leg strakes (non-nodal leg sections) by welding their ends to the node barrels. In small nodal assemblies the braces have coped ends welded directly to the node barrel, and in larger assemblies the braces are cut square and welded to a short stub which is often thicker than the brace itself.
All structural welds in a jacket structure are full penetration, resulting in a watertight construction.

The submerged steelwork is protected against corrosion by sacrificial anodes, by impressed currents or by a combination of both systems. In the splash zone, the jacket leg sections have to be specially protected against corrosion. The legs and bracings in the splash zone are by definition unable to gain cathodic protection and as a result often have their basic wall thickness increased by 10 to 12mm to counter corrosion losses. The splash zone thickening of the legs and bracings, risers and caissons is known as 'corrosion protection'.

Platforms with drilling facilities feature conductor guides and associated horizontal bracings at various elevations. Conductor bracings appear in the plan bracing levels of the jacket and also in the MSF framing levels. Consideration should be given to fire loading effects on conductor bracing especially in the elevations where the bracing can be out of the water and hence liable to fire. Considerations for fire design should be given to all parts of the substructure which are located out of water.

2.1.2 Deck and Module Support Frame Structures

The concept of a module support frame was introduced in the design of barge-launched structures such as Conoco Murchison and Shell North Cormorant where a substantial framework was required to connect the jacket to the modules.

In later designs the concept has been altered considerably, but the detail is still to be found in many fixed steel platforms where there is a need to provide a deck structure to bring support from the jacket structure to the module support level, which must be clear of the extreme wave height.

In self-floating tower designs such as BP Magnus and Chevron's Ninian Northern there is no MSF, but the upper part of the tower includes a deck section.

The design of the module support frame or deck structure has predominantly been the realm of jacket design specialists and as a result many of the steel types found in the jacket structure are to be found in the module support frame. The dominant steel types in the MSF are BS 4360 Grades 50 and 43 (and the BS 7191 equivalents).

The top rail or upper chord of a MSF or deck structure may either be a tubular section as in Conoco's Murchison, or a plate girder as found in the BP Clyde design. The top rail of the MSF is an extremely important structural element and is generally fabricated from either Grade 50 or Grade 55 steel. In recent projects the use of RQT steel for the MSF top rail has been suggested.
There are often utilities present in the MSF structure and so the steel types will include those for the jacket, plus some of the piping and vessel materials found in the modules themselves. Stairways are found in the MSF and may be fabricated from rolled sections or from SHS (square hollow sections) and RHS (rectangular hollow sections) using steel Grades 43 and 50.

2.1.3 Module Structure

Compared with the substructure, there are less variations in the basic design and installation of typical production modules. The maximum size of a module has been limited by the available lifting equipment to install them offshore. As crane vessel maximum lift loads have increased, module designers have sought to optimise the number of offshore lifts.

As a result, platforms built of multiple modules and installed at a similar date will tend to have module weights and sizes which are roughly comparable. In the southern North Sea, the gas platforms are generally much smaller than the oil platforms to be found further North and so the gas platform topsides may consist of only one deck. The British Gas Rough storage development is a notable exception to this rule.

In general terms, there has been a tendency to use a higher proportion of Grade 50 and Grade 55 steels in the more recent (1982-90) module designs, resulting in an absence of Grade 43 steels except in minor structural details. In older structures (1974-82), the highest structural grade of steel employed was often Grade 50, and a higher proportion of the total structural tonnage would be of Grade 43 steel than is found in, say, a 1990 design. It should be remembered that the higher stress grades will not be practical when deflection criteria govern the design of elements - the "E" value (Young's modulus) being similar for Grades 43, 50 and 55 steel.

A module may follow one of two possible structural framing patterns. In the shoe-box type design, the external frames form the basis of the steel skeletal structure, with cross bracings installed transversely between module reaction points. The lower floor of the module must take the loads imposed by boeys at load-out and is often of a deep plate girder design, with the plate girders running transverse to the module sides. The roof of the module will be subjected to racking forces during lifting operations and will consequently be braced with diagonal elements, which are often of tubular section so as to minimise buckling effects.

When the module reaches certain key proportions, the box type of construction is no longer viable and internal trusses have to be introduced to carry the increased floor loads. Since 1984 there has been a tendency for module designs to use cast steel padeyes for the attachment of lifting cables to the structure during offshore installation. However, these lifting lugs are often cut off or play no significant role in the in-service condition and the occurrence of cast steel in module structures is of minor importance.
However, designers have recently suggested the use of cast steel module nodes as a method of increasing the beneficial heat sink effect in a fire.

In an integrated deck design such as the Mobil Beryl “B” platform, the form of the modules is quite different from the standard design with the modules taking the form rather similar to an extended MSF structure.

Despite the variations in structural form, the primary steelwork in module structures is fabricated from a combination of the following materials:

- BS 4360 Grade 50 and 55 or equivalent for plate girders and for rolled tubular column sections. Plate girders are most commonly found in the lowest deck of the module where they are required for load-out and to take the bending moments between support points.

- BS 4360 Grade 50 and 55 for universal beam and universal column sections used in the module superstructure.

- API Grade 5L piping used as framing bracings and as column structures.

- Roller Quenched and Tempered steels.

The secondary steelwork is fabricated from a number of different elements, shapes and material types.

Flooring and bulkheads are made from plate steel in the general range 4 to 12mm thick (and above), which may be stiffened with plate stiffeners, angles, channels, UB's and bulb-flats. Grade 43C or equivalent is largely used for this purpose, although there is a tendency to use Grade 50 steels in more recent designs.

Internal module flooring, particularly on mezzanine floors is often made from grating. The grating is hot-dipped galvanised Grade 43 steel, uncoated for internal use and painted to a high standard for external use. The flooring support beams are fabricated from channel and angle sections, and the stringers and support beams are either channels or the smaller series UB's. Walkway support steel is invariably fabricated from Grade 43C steel.

Tubular steel sections of Grade 50 are used in the design of flare-booms, which may be of quite considerable size in some designs. The smaller sections will be of API Grade 5L. Stainless steel has been suggested for use in the fabrication of certain flare-booms.

Tubular steel sections, and miscellaneous rolled sections are used in the fabrication of drilling derricks and cranes. BS 4360 50D and 43C are the dominant material types.

Pipe supports are fabricated from miscellaneous rolled sections and are often welded directly to the web or to the flanges of plate girders and universal beams forming the primary structure. Dominant grade of material used is BS 4360 Grade 43C.
2.2 Secondary and Systems Steels

2.2.1 Pipework and Vessels

The steels commonly used in pipework and vessels are as follows:

- **Carbon steels** - for general service pipework.
- **Boiler steels** - for high pressure and temperature applications.
- **Stainless steels** - used for high temperature service pipework and vessels and also where high cleanliness is required, particularly in 'lube and seal' oil systems.

For process piping the following grades are in common usage:

- **API 5L Grade B**

See Tables 2.2 and 2.3 for details of ASTM A106 and ASTM A333 steel grades respectively.

**BS 3602 Part 1 1987** [13] covers the specification of steel pipes and tubes for elevated temperature performance and gives minimum proof stress values at temperatures up to 450°C.

Carbon Steel in Pressure Vessels

**BS 1501** [14] gives a specification for steel plate to be used in fired and unfired pressure vessels, and includes a proof stress value for the temperature range 150°C to 400°C. The specification includes 3 grades, 360, 400 and 430, these referring to the ultimate tensile strength and not the yield. For example a 110mm thick plate with a yield of 196 N/mm² can be described as Grade 400.

**BS 1501 Part 2** [14] gives the details of Alloy steels as follows:

- Type 243 0.3% molybdenum steel
- Type 271 manganese-chromium-vanadium steel
- Type 281 nickel-chromium-molybdenum-vanadium steel
- Type 620 1% chromium 0.5% molybdenum steel
- Type 622 Grade 515 2.25% chromium 1% molybdenum steel
- Type 622 Grade 690 2.25% chromium 1% molybdenum steel
- Type 503 Low temp 3.5% nickel steel
- Type 510 Low temp 9% nickel steel
- Type 828 3% nickel-chromium-molybdenum steel.
BS 1501 Part 2 steels can be used for high temperature service and their performance is specified in terms of an average stress to produce rupture in a service period (10,000 to 250,000 hours) at a particular temperature.

The maximum design temperature varies according to the steel type, being a maximum of 630°C for steel types 620, 621, 622 and 660 for 10,000 hours service. It should be stressed that 'boiler steel' endurance data is not the same class of data as the fire-resistance data described in Section 3 of this report.

**Stainless Steels for Pipework and Vessels**

ASTM A312 [15] Type 316 - seamless and welded austenitic stainless steel pipe. Nickel content 10 to 15% and chromium 16 to 18%; tensile strength 485 N/mm², yield 170 N/mm².

ASTM A312 [15] UNS 31254 solution annealed with 6% molybdenum. This is a 17.5% to 18.5% nickel and 19.5-20.5% chromium alloy, supplied in seamless and straight-seamed welded pipes.


ASTM A269 [17] Type 316 solution annealed (tubing from instrument tappings and hydraulic lines). This is a small bore stainless steel grade, and its properties are defined in terms of a hydrostatic pressure test. The nickel content varies between 10% to 15% and the chromium content varies between 15% to 18%.

ASTM A358 [18] UNS 31254 - this is an electric fusion welded austenitic chromium-nickel alloy steel pipe for high temperature service. It is solution annealed with 6% molybdenum, and may be used for pressure vessels; yield strength 300 N/mm², tensile 650 N/mm².

BS 1501 Part 3 [14] specifies steels for pipework and vessel applications which have particular corrosion and heat resisting properties. The standard deals with 'stainless' grades with a 16.5% chromium content or higher.

**2.2.2 Cladding and Wall System Steels**

The cladding steels used in module wall systems fall largely into two divisions - self-supporting and fixed systems. Self-supporting walls are often made from relatively thick plate (3 to 8mm) which is formed into deep corrugations so as to improve the plate stability and bending resistance. Self-supporting walls may form internal firewalls and blast-rated panels. Both stainless and carbon steel types are in current production. Stainless Grade 316S31 and BS 4360 Grade 43A are commonly specified.

In some systems internal insulation is employed to enhance the fire-rating and further permutations arise when thin metal finishing panels are detailed for architectural purposes.
Alternatively a wall may be fabricated using a rolled steel section as the supporting medium (in the form of Grade 50 UB's and UC's), with thin walled corrugated cladding attached. The cladding will generally be cold-formed steel. (See Table 2.4 for details).

Composite fire-resisting walls are fabricated from metal casements with linings of fire protective materials, such as blankets, boards or loose-fill materials. (See Reports on Work Packages FR3 and FR4).
3. PROPERTIES OF STEELS AT ELEVATED TEMPERATURES

3.1 Test methods

Before any design can be performed, specific properties of the material under consideration need to be known. Engineers designing in steel need two basic measures - the Young's modulus (E) of the steel and the yield strength (\(F_y\)) of the steel. These are obtained from tensile tests in which a defined test specimen is strained at a given rate and the load applied is measured. The relationship between stress and strain is plotted and the slope within the linear portion is defined as Young's modulus; the point of departure from linearity being defined as the yield strength. Note that mild steels can exhibit both an upper and a lower yield point whilst stainless steels do not have a distinct yield point. Typical stress-strain curves are shown in Figure 3.1.

At the time of a fire a steel structure will be carrying load. For many structural elements the load that is present does not appreciably change during the fire; however, for structural elements subject to thermal restraint, an increase in load can be expected. This is due to the effects of thermal expansion and restraint.

In order to obtain the material properties at elevated temperature there are two common tests available. A standard tensile test can be carried out at a specified elevated temperature. This is known as an isothermal test. Alternatively a test can be carried out to monitor extension in which the steel is loaded and then heated whilst the load is maintained at a constant level. This test is known as an anisothermal test.

Typical strain-temperature curves from an anisothermal test are shown in Figure 3.2. Theoretically a test could be carried out in which the load and temperature were made to follow any path, but few facilities exist for such testing.

In deciding which test method to use, three factors must be considered which are not as critical at normal temperatures.

Firstly, certain steels undergo heat treatments during manufacturing which can be related to carefully controlled rolling. In an isothermal tensile test, the sample of steel is first heated and then strained. Those properties which have been explicitly improved by rolling and heat-treatment can be expected to be reduced during the test. However, the loss of such enhanced properties will be more obvious above a certain threshold temperature than when the test is performed at a lower temperature.

Secondly, at high temperatures, the rate of strain is more critical than at normal temperatures and a false high value of elevated temperature strength can be obtained. This effect is more pronounced at low strains. It is therefore important to record both the stress and the strain measured in a test. See for example the representation of test data in Eurocode EC3 [2].
Thirdly, the rate of heating is more important in the anisothermal test method. For long heating periods the measured strains incorporate a degree of creep. The effect of creep is not considered to be significant for short duration fires. Onshore fire codes [1,2] ignore creep for up to 4 hours.

With the faster rates of heating that could be expected in offshore (hydrocarbon) fires, creep may not be significant but it will depend on the heating rate and duration of the fire.

Of the two methods, by far the most commonly used method is the isothermal tensile test. Standards exist in many countries for this test, see for example BS 3688 [19].

The anisothermal test was developed specifically for obtaining properties for fire calculations and is not routinely used. It was used, however, as the basis for deriving the elevated temperature properties which are quoted in the European and British onshore codes [1,2]. Reasons that the test is not used routinely include the complexity of the test equipment and that the procedure for carrying out anisothermal testing is not defined in any code.

For normal structural steels it has been found that data obtained from an isothermal test method best describes the behaviour of steels in a fire. In an anisothermal test, the initial elastic behaviour of steel is underestimated. This is because an initial stress greater than the 'room temperature' yield stress cannot be applied. Also the effect of work hardening cannot be measured in an anisothermal test method. Both these effects have been taken into account in the draft European code EC3: Part 10 [2].

3.2 Creep

Creep is the time-dependent straining of a material. When materials are loaded to stresses close to their yield point over a prolonged period of time, creep will occur. Creep causes deflections to increase although the applied load is kept constant.

In determining the properties of steel at elevated temperatures, it is possible that the high temperature/near failure performance of steel can be strongly influenced by creep. In some cases where engulfment of a steel component by fire is partial or there is strong radiation from a nearby fire, the temperature of the steel may stabilise such that failure is imminent. Although the failure stress has not been exceeded, lengthy exposure at that temperature can cause failure due to creep. Therefore it is important that creep be considered, whilst realising that at high temperatures, rapid plastic failure/collapse shall generally predominate.

In onshore studies it is recognised that probably creep effects rather than stress/Young's modulus effects lead to large deflections and subsequent ultimate collapse experienced in steel framed buildings under fire loads.
Rubert and Schaumann [20] explain how the total strain is made up of three components:

- thermal strain of the material (thermal elongation)
- stress dependent strain (Young's modulus effect)
- warm-creep strain (Pure creep).

Because these three factors can be confused in an experimental test, it is important to know how the warm-creep term has been allowed for. In an anisothermal testing scheme, creep effects will be largely associated with heating rates (See Table 3.3).

In a 'real' fire some unprotected members might be subjected to substantial heat fluxes resulting in rates of temperature rise in excess of 100°C per minute - under these conditions, creep effects can be ignored. However, for large cross section steelwork or where the heat flux to the steel is such to produce considerably lower heating rates, the performance of that component could include creep effects that might increase structural deflections. The latter circumstances might arise in insulated steel members or unprotected steelwork exposed to radiation from a fire rather than direct flame impingement. From experiments carried out, typical steel heating rates with passive fire protection can be as low as 4°C per min [21]. The effects of heating rates and creep are discussed further in Section 3.3.1.

### 3.3 Properties of Specific Steels at Elevated Temperatures

For all the steels studied, recommended design properties at elevated temperatures are given. The strength quoted is based upon tensile tests. However, similar reductions in strength may be assumed for compression and shear.

#### 3.3.1 Mechanical Properties

The elevated temperature properties are based on British and European data and are as specified in the draft of EC3: Part 10 (April 1990). This data is based on anisothermal test data supplemented with some isothermal test data.

Generally it may be assumed that the effect of creep is included in the stress-strain relationships. Where information on creep is known it will be given.

The stress-strain curves for steel at elevated temperatures are formed in four parts. These are:

a) a linear elastic part  
b) an elliptical transition part  
c) a plastic part  
d) a linear reduction part.
Each part of the curve is defined mathematically. The various parameters required to define the curve are illustrated in Figure 3.3 and the necessary formulae are given in Table 3.1. The variations of modulus of elasticity and stresses are given in non-dimensional form in Table 3.2. Intermediate values may be obtained by linear interpolation.

Although not included in the draft of EC3, Part 10, the European Committee have proposed a modification to take strain hardening into account. For temperatures below 400°C and in applications where local buckling is not expected, an improvement in strength is obtained (Figure 3.4). See Ref [3] for further details.

The proposed EC3, Part 10, data is extremely close to the British Steel data given in BS 5950 Part 8. In BS 5950 Part 8 the strength of steel at elevated temperatures is given in terms of a strength reduction factor to be applied to the normal design strength. This factor is given for strains of 0.5%, 1.5% and 2% for a range of temperatures. The BS 5950 Part 8 data is compared with EC3 Part 10 data in Figure 3.5.

The EC3 and BS 5950 Part 8 data are based upon a heating rate of 10°C per minute. British Steel have compared steel strength measured at different heating rates and proposed a modification to take account of other heating rates. The modification is applied to the temperature when calculating the effective yield and is given in Table 3.3. This is a method for allowing for the small effects of creep in fire calculations.

For example, to obtain the stress-strain curve at 420°C for a heating rate of 20°C per minute, the effective yield is obtained using a temperature of 420°C - 15°C, i.e., the effective yield is higher at the adjusted temperature. For 5°C per minute the temperature is increased and lower properties are obtained.

It should be noted that this correction table applies to heating rates tested for onshore (cellulosic) fires requirements. No comparable table is available for offshore hydrocarbon fires. It is suggested that Table 3.3 could be used with caution for insulated elements.

It is possible that heating rates greater than 20°C/min could occur. This applies particularly where there is high surface area relative to volume, low-level or damaged insulation or where there is a high fire intensity. A hydrocarbon jet fire is an example of the latter. Data on temperature modification at rates in excess of 20°C/min may therefore be needed. At present no data on faster heating rates is available.

3.3.2 Thermal Properties

Coefficient of linear expansion (α)

In the range up to 750°C α may be taken as 14 x 10^-6 per degree Centigrade. A graph illustrating the thermal elongation of steel is illustrated in Figure 3.6.
Specific Heat

For simple calculations a value of 520J/kg°C may be used. This corresponds to a temperature of about 185°C and is useful provided the steel temperature does not exceed 500°C. A graph illustrating the variation of specific heat is shown in Figure 3.7. Note the important phase change at about 730°C.

Thermal conductivity

For simple calculations a value of 45 W/m²K may be used. This value corresponds to a temperature of 273°C and is useful provided the steel temperature does not exceed 500°C. A graph illustrating the variation of thermal conductivity is shown in Figure 3.8. This data can be used for all low carbon grades of steel, including RQT steels.

Emissivity (ε)

Hot steel will emit heat in the form of radiation. The coefficient is therefore used when calculating heat loss. The appropriate value for bare steel is between 0.5 and 0.9, depending on the surface finish, corrosion and thermal history.

Absorptivity (a)

Radiation incident on the surface of steel may be either absorbed or reflected. The percentage of radiation absorbed by the surface is defined as the absorptivity. For bare steel values of between 0.5 and 0.9 are used, depending on the surface finish, corrosion and thermal history.

3.4 RQT Steels

3.4.1 Mechanical Properties

The elevated temperature properties of RQT steels are dependent upon the chemical composition and production process route. It is difficult to give general guidance for design purposes and engineers are advised to consult the manufacturer or supplier. Properties which are available will almost certainly be based upon isothermal testing and published data may be limited to the 0.2% or 0.5% proof stress.

To illustrate the difficulty in giving general (applicable) guidance the 0.2% proof stress of British Steel's RQT 501 is plotted in Figure 3.9. It can be seen that at about 400°C the effect of the chemical composition becomes extremely marked.

In Figure 3.10 the 0.5% strain strength reduction factor for an Australian steel 'Bisalloy 80', produced by BHP, is compared with the strength reduction factor taken from EC3. Below 500°C the strength reduction factors are very similar, but above 500°C the strength of the RQT steel appears to fall off more rapidly.
The temperature at which the RQT steel begins to lose strength is dependent on the tempering temperature and this varies from steel to steel. BHSP state that for the range of RQT steels they produce the tempering temperatures varies between 177°C and 543°C. It follows that the temperature at which they rapidly lose strength will vary in the same way.

3.4.2 Thermal Properties

In the absence of specific data, the thermal properties of RQT steels may possibly be the same as for the common structural steels.

3.5 Stainless Steel

Stainless steel is used in various forms in offshore structures. Structurally it is little used, but it is used for cladding systems and pressure vessels and pipework.

3.5.1 Mechanical Properties

The elevated temperature properties of two of the more commonly used steels are plotted in Figure 3.11 and compared with the EC3 steel data. In common with many of the high alloyed steels the stainless steels show initially a rapid decrease in strength, but the rate of loss decreases and at high temperatures they show an appreciable strength compared with the more common structural steels. The initial loss of strength may not actually be as great as it seems. The data for stainless steel is effectively minimum guaranteed values, whereas the EC3 data is closer to average data. If similar data was available it is likely that the stainless steel would appear to perform better below 250°C.

In Figure 3.12 three stainless steels are compared to illustrate a problem in using elevated temperature data for high alloyed steels.

The three grades of stainless steel perform differently at elevated temperatures and the degree of variation is greater than that which has been found for low carbon steels. In consequence it is important that two concepts are clearly pursued when stainless steel data is used. These are:

- does the data relate to minimum or average material behaviour?
- does the data match the grade of material which has been selected for analysis?

It is clearly important to make sure that the data being used applies to the steel being specified.
In a recent paper [22] the influence of hydrogen upon stainless steel microstructure was examined. There is a strong indication that the heat-resisting strength of stainless steel could be influenced by the presence of hydrogen. A similar deleterious effect [22] was recorded for hydrogen in stainless steels when the strain-rate effect was examined. Hydrogen is more likely to pass into the microstructure of stainless steels in pressure vessels. The API document 941 [23] gives further data on the subject.

3.5.2 Thermal Properties

The thermal properties of stainless steels are not the same as for the common structural steels; the most significant difference being in the coefficient of expansion which is somewhat greater for stainless steels. The thermal properties are given in Table 3.4.

3.6 Pressure Vessel Steels

Steel for pressure vessels are typified by British Standard BS 1501. This standard is in three parts:


Part 2 Steel for pressure purposes: plates, sheet and strip; specification for alloy steels.


These standards are reviewed below and indicate that elevated temperature properties are product specific. However, the Metals Handbook [24] does give an exhaustive reference to the variations available for a large range of metallic materials, and can be used to augment the properties given in the standards. Whether all the 'design data' which is available for pressure vessel steels can be used for fire design is debatable. Some of the data will be conservative, and may require correction for (a) heating rates and (b) lower bound as opposed to 'average' stress values.
3.6.1 Mechanical Properties

BS 1501: Part 1
Steels for fired and unfired pressure vessels: plates, sheet and strip. Specification for carbon and carbon manganese steels

This part contains specifications for steels that are similar to the normal structural steels, but have guaranteed properties at elevated temperatures. The properties of a typical steel Grade 223 (490) are compared with the EC3 steel properties in Figure 3.13. The comparison is based on the 0.2% proof stress. Although in the temperature range 20°C-400°C the BS 1501 Part 1 steel is weaker than the EC3 steel, for temperatures in excess of 400°C the reverse is true. However care must be made in comparing like with like. BS 1501 Part 1 properties quoted are guaranteed, whereas the EC3 steel data is much closer to average properties.

BS 1501: Part 2
Steels for pressure purposes: plates, sheet and strip. Specification for alloy steels

This part contains specifications for alloy steels containing appreciable amounts of chromium and molybdenum compared with the Part 1 steels. These have the effect of improving the elevated temperature properties. However the amount of improvement is greatly dependent on the particular grade.

In Figure 3.14 a comparison is made for a BS1501: Part 1 steel, to BS1501: Part 2 steels and EC3: Part 10; loss of strength at elevated temperature being highlighted. However care must be taken in comparing like with like (see comment for BS1501: Part 1 steel). From Figure 3.14 the two BS1501 Part 2 steels (Grade 271 and 620) have markedly different properties at elevated temperatures. It is often found it is not possible to assume that steels with similar specifications behave the same at elevated temperatures. Designers should be aware of this.

BS 1501: Part 3
Steels for pressure purposes: plates, sheet and strip. Specification for corrosion and heat-resisting steels

These steels are types of stainless steel and are discussed in Section 3.5.

3.6.2 Thermal Properties

The thermal properties of steels to BS 1501: Part 1 and Part 2 may be assumed to be the same as for the common structural steels. For steels to Part 3 see Section on stainless steel (3.5).
3.7 Steels with Enhanced Properties at Elevated Temperatures ('Fire-Resistant' Steels)

Data on two types of steels that can reasonably be described as fire-resisting are given here.

3.7.1 Mechanical Properties

Nippon Steel SM50A-NFR

This steel has a nominal yield strength of 354 N/mm² with a tensile strength of 570 N/mm². Nippon Steel Corporation publish elevated temperature stress-strain curves for this steel and these are reproduced in Figure 3.15.

In Figure 3.16 the stress temperature curves for SM50A-NFR and the equivalent low carbon steel data are compared. The Nippon Steel appears to have better properties which would make it attractive for many design situations. However a true comparison will only be possible when samples are subjected to the same tests. The exact test procedures used by Nippon Steel are not yet available.

British Steel PLC "Ducol W30"

British steel produce a steel with good high temperature properties which is included in BS 1501: Part 2 as Grade 271 steel. It has the brand name of "Ducol W30". 0.2% proof stress values up to 500°C are given and these are plotted in Figure 3.17 and compared with the equivalent EC3: Part 10 steel. The values given in BS 1501 are minimum guaranteed values and are therefore not directly comparable with those of normal structural steel, but from the figure it can be seen that above 230°C "Ducol W30" has much improved properties. At low temperatures the "Ducol W30" appears to lose strength quickly compared with the normal structural steel. This is due to the fact that the properties are minimum guaranteed and some steel samples may show this reduction. On the other hand some samples will show an increase in strength. The values used in EC3 are average strength reduction values. It is likely that if "Ducol W30" was tested to obtain the equivalent EC3 type information the low temperature properties would show an improvement and the higher temperature properties would also show some improvement. Although at 500°C "Ducol W30" appears to have improved properties it is likely that differences between it and the normal structural steels will diminish rapidly between 600°C and 700°C.

3.7.2 Thermal Properties

In the absence of specific data, the thermal properties of 'Fire-Resistant' steels may possibly be the same as for the common structural steels.
3.8 Welds and Bolts

There is little information relating to the elevated temperature properties of welds or bolts; BS 5950: Part 8 [1] recommends that a strength reduction factor of 80% corresponding to a 0.5% steel strain. The strength reduction factor based on this approach is illustrated in Figure 3.18.

British Steel PLC are at present carrying out research in this area and expect to report in 1991.
4. CURRENT POSITION

4.1 General

In this report the available elevated temperature properties of many of the steels used offshore have been summarised. The data is both of variable quality and quantity depending on the source of the data and the type of steel. For the common structural steels (BS 4360 Grades 43 and 50 and similar steels) the data is both extensive and known to be suitable for use in fire calculations. For the other steels the data has largely been produced for non-fire purposes and is not as extensive. High temperature data is given in many steel standards where the steel is expected to be at high temperatures during normal use. However, where a steel is not intended to be subjected to fire during normal use, the available high temperature data is not ideal for fire purposes.

An important finding has been that, except for the common structural steels that are used onshore, the elevated temperature data available are generally given as minimum guaranteed values. They are therefore conservative when compared with elevated temperature data for common steels, which are closer to average properties.

Minimum guaranteed values are quoted in the standards when steels are to be used for elevated pressure vessel service. When these data are used directly for the design of non-pressure service structural components, there will tend to be an underestimate of the likely performance in fires.

4.2 The Common Structural Steels

The elevated temperature properties for the common steels (BS 4360 Grades 43 and 50 and similar steels) have been established for onshore fire design and are generally suitable for offshore work; a possible exception is when the steel is heated extremely quickly, say to 600°C in 5 minutes. The fastest heating rate examined onshore was about 20°C per minute. At the much faster heating rate the onshore data would be conservative. This assumption is based on Table 3.3 - Temperature Modification for Different Heating Rates. The best sources of data are BS 5950: Part 8, EC3: Part 10 and EC4: Part 10.

The data contained in BS 5950 is based on tests carried out by British Steel PLC and the data in the Eurocodes is based upon the British data supplemented by test data from France, Germany and Luxembourg. In time the national design codes throughout Europe will be replaced by the Eurocodes, so it would seem logical to use the EC3 and EC4 data for design purposes.

Note that part of the data in EC3 Part 10 is presented in a semi-mathematical form, thereby allowing straightforward adaptability in computerised analysis. Also the Eurocodes provide comprehensive stress-strain curves for temperatures up to 950°C, whereas in BS 5950, strengths are only defined for a small range of strains.
of more significance is the range of stresses that are covered by the different sources. The British Steel data is reported for twenty strains from 0.001 to 0.02, with temperature intervals of 50°C up to 900°C, and as such is amenable to use by large deflection analysis programs. The British Steel data is shown in Figure 4.1 and Figure 4.2. The BS 5950 Part 8 [1] data is only available for three reference strains as given in Table 1.1. The Eurocodes [2,3] quote data for 235 N/mm² and 355 N/mm² low carbon steels at thirty strains from 0.0005 to 0.02, and for temperatures in the range 100°C to 800°C, using steps of 100°C.

Comparison has been made of the specimen values of British Steel and Eurocode data (see Figure 3.5) and it is concluded that, although the methods would yield slightly different answers, the values for temperature-dependent yield stress are very similar and either code could be used for meaningful fire condition analysis.

Perhaps the most comprehensive data source is SCI Handbook to BS 5950 Part 8 [25] which tabulates data for the strains of up to 2% with data available for Grade 43A and Grade 50B steel, with data quoted at temperatures of 50°C to 950°C at 50°C intervals.

4.3 RQT Steels

High strength RQT steels are beginning to be considered for parts of offshore structures where their high strength and low temperature toughness makes their use attractive.

Detailed information on the high temperature properties of Roller Quenched and Tempered steels is sparse and in any case tends to be product specific. This is illustrated in Figure 3.9 where two variants of RQT 501 manufactured by British Steel are compared. In the figure the two nominally similar steels, but with slightly different chemical compositions, can be seen to have different high temperature properties. Another steel examined is a steel produced by BHP of Australia (see Figure 3.10). This steel shows the importance of the tempering temperature. Initially the BHP RQT steel appears to perform as well as the common structural steel, but at temperatures in excess of the tempering temperature (above 650°C) the properties fall off quickly.

Note that data available was limited to a maximum strain of 0.5% and no stress-strain curves are available. Also no data was found relating to the variation of Young's modulus with temperature.

It is concluded that with RQT steels the elevated temperature properties are product specific and any general guidance could be misleading.

4.4 Stainless Steels

Stainless steels are used offshore for cladding, heat shields and in process plant. They are at present not used for any structural components.
A large body of data exists on the high temperature properties of stainless steel. It is virtually all confined to process plant steel and is limited to 0.2% proof stress values or values of strength at 0.5% strain.

Insufficient data was found to construct stress-strain curves or the variation of Young’s modulus with temperature.

At high temperatures stainless steel has very good properties when compared with the common structural steels. This is illustrated in Figure 3.11. In this figure the strength of stainless steel appears to initially reduce rapidly. This is discussed in Section 3.5 of the report and is partly due to test methods and degree of confidence in strength values. The properties of stainless are, like the properties of the RQT steels, product specific.

The published data, as quoted in steel standards, is useable in fire analysis, but the data can be rather incomplete and hence certain analytical procedures may be limited by the range of data which is currently available.

4.5 Pressure Vessel Steels

The properties of three types of pressure vessel steels have been reported.

The carbon/manganese steels are broadly similar to the common structural steels, but the high temperature properties quoted in the standards are appreciably worse than the properties of the common structural steels. The available data is in the form of 0.2% proof stress values and are minimum guaranteed values.

The alloy steels have much better performance at high temperature, but appear to have poorer performance at below about 200°C. This is because the data is 0.2% proof data and the values are minimum guaranteed values. At high temperatures the alloy steels have very good performance and one particular steel, BS 1501: Part 2 Grade 271 "Ducol", can be classed as a ‘fire-resistant’ steel. Although alloy steels perform well, the properties at high temperature are product specific and data used must relate to the specific steel being used.

The pressure vessel stainless steels are considered under the heading of stainless steel.

It is concluded that for pressure vessel steels, the elevated temperature properties are product specific and any general guidance could be misleading.
4.6 Steels with Enhanced Properties at Elevated Temperatures ('Fire-Resistant' Steels)

Steels with good high temperature properties have been available for many years; British Steel's "Ducol" is a good example.

Recently Nippon Steel announced that they were producing a fire-resistant steel, NFR50A, with significantly better properties than the common structural steels.

Based on the available information, both these steels appear to have enhanced properties at temperatures in the range 300°C to 500°C. The data relating to "Ducol" is 0.2% proof stress values and for NFR50A the full stress-strain curves are given.

It is concluded that these 'fire-resisting' steels may have a role to play offshore, especially when low steel failure temperatures are being used (below 450°C). It is reported that the extra cost in using these steels is in the region of 30% and the steels can be welded without much trouble. However some doubt exists concerning the low temperature impact strength which may be required for some applications. More and better data is required.

4.7 Data for Explosion/Fire Interaction

The material properties data required for explosion/fire interaction design should include the following:

- the variation of Young's modulus with temperature
- the variation of stress-strain characteristics with temperature
- the variation of stress-strain characteristics with the rate of strain (change of strain with time).

Further information is presented in the Reports on Work Packages FR6 and BR4.
5. AREAS OF UNCERTAINTY

It is clear from the study that insufficient suitable information exists at present to allow engineers to carry out design calculations on any steel other than the common structural steels. To design adequately or analyse a structure for fire, stress-strain curves for steel are required for strains up to at least 5% and for temperatures up to 700°C–800°C maximum. This information is only available for the most common structural steels in the Eurocodes.

However, the available data is generally limited to 0.2% proof stress values and needs extending to full stress-strain curves. The basis on which the data is quoted, Average or Minimum Guaranteed values, needs unifying such that meaningful comparisons can be made. Ideally the tests that were carried out to obtain the Eurocode steel properties data should be repeated for all the types of steel that may be required to be designed/analysed to take into account elevated temperatures. Having gained the knowledge in deriving that data, it should be possible to use a shortened test programme for many of the steels.

Before steels with enhanced properties at elevated temperature (‘fire-resistant’ steels) can be confidently used, further investigation from both the elevated temperature properties standpoint and the low temperature impact properties standpoint must be made. In addition, although beyond the scope of this Project, the economics of using these ‘fire-resistant’ steels needs to be studied.
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<table>
<thead>
<tr>
<th>Temperature</th>
<th>0.2% Strain</th>
<th>0.5% Strain</th>
<th>1.5% Strain</th>
<th>2.0% Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.940</td>
<td>0.970</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>150</td>
<td>0.898</td>
<td>0.959</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>200</td>
<td>0.847</td>
<td>0.946</td>
<td>1.000</td>
<td>1.000</td>
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<tr>
<td>250</td>
<td>0.769</td>
<td>0.884</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>300</td>
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<td>1.000</td>
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<tr>
<td>350</td>
<td>0.626</td>
<td>0.826</td>
<td>0.968</td>
<td>1.000</td>
</tr>
<tr>
<td>400</td>
<td>0.600</td>
<td>0.798</td>
<td>0.956</td>
<td>0.971</td>
</tr>
<tr>
<td>450</td>
<td>0.531</td>
<td>0.721</td>
<td>0.898</td>
<td>0.934</td>
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<tr>
<td>500</td>
<td>0.467</td>
<td>0.622</td>
<td>0.756</td>
<td>0.776</td>
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<tr>
<td>550</td>
<td>0.368</td>
<td>0.492</td>
<td>0.612</td>
<td>0.627</td>
</tr>
<tr>
<td>600</td>
<td>0.265</td>
<td>0.378</td>
<td>0.460</td>
<td>0.474</td>
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<tr>
<td>650</td>
<td>0.186</td>
<td>0.269</td>
<td>0.326</td>
<td>0.337</td>
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<tr>
<td>700</td>
<td>0.112</td>
<td>0.186</td>
<td>0.223</td>
<td>0.232</td>
</tr>
<tr>
<td>750</td>
<td>0.085</td>
<td>0.127</td>
<td>0.152</td>
<td>0.158</td>
</tr>
<tr>
<td>800</td>
<td>0.059</td>
<td>0.071</td>
<td>0.108</td>
<td>0.115</td>
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<tr>
<td>850</td>
<td>-</td>
<td>0.045</td>
<td>0.073</td>
<td>0.079</td>
</tr>
<tr>
<td>900</td>
<td>-</td>
<td>0.030</td>
<td>0.059</td>
<td>0.062</td>
</tr>
<tr>
<td>950</td>
<td>-</td>
<td>0.024</td>
<td>0.046</td>
<td>0.052</td>
</tr>
</tbody>
</table>

Table 1.1
Strength Reduction Factors for Steel
to BS 4360 Grades 43 and 50

Notes
1. Intermediate values may be obtained by linear interpolation
2. For temperatures higher than the values given, a linear reduction in strength to zero at 1300°C may be assumed
3. Young's modulus (E) may be obtained from the table using finite difference methods
<table>
<thead>
<tr>
<th>BS 4360 GRADE</th>
<th>YIELD Stress in N/mm²</th>
<th>CHARPY TEMP in °C</th>
<th>CHARPY ENERGY J (V Notch)</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>43C</td>
<td>255</td>
<td>0</td>
<td>27</td>
<td>AS ROLLED</td>
</tr>
<tr>
<td>50D</td>
<td>340</td>
<td>-20</td>
<td>27</td>
<td>NORMALIZED</td>
</tr>
<tr>
<td>50DD</td>
<td>340</td>
<td>-30</td>
<td>27</td>
<td>NORMALIZED</td>
</tr>
<tr>
<td>50EE</td>
<td>340</td>
<td>-50</td>
<td>27</td>
<td>NORMALIZED</td>
</tr>
<tr>
<td>50F</td>
<td>340</td>
<td>-60</td>
<td>27</td>
<td>QUENCHED AND TEMPERED</td>
</tr>
<tr>
<td>55EE</td>
<td>415</td>
<td>-50</td>
<td>27</td>
<td>NORMALIZED</td>
</tr>
<tr>
<td>55F</td>
<td>415</td>
<td>-60</td>
<td>27</td>
<td>QUENCHED &amp; TEMPERED</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BS 7191 GRADE</th>
<th>YIELD STRESS in N/mm²</th>
<th>CHARPY TEMP in °C</th>
<th>CHARPY ENERGY J (V Notch)</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>275D</td>
<td>265</td>
<td>-20</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>275E</td>
<td>265</td>
<td>-40</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>275EZ</td>
<td>265</td>
<td>-40</td>
<td>40</td>
<td>Z=THRO THICKNESS PROPERTIES</td>
</tr>
<tr>
<td>355D</td>
<td>345</td>
<td>-20</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>355E</td>
<td>345</td>
<td>-40</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>355EM</td>
<td>345</td>
<td>-40</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>355EMZ</td>
<td>345</td>
<td>-40</td>
<td>50</td>
<td>M=MODIFIED BS4360 STEEL</td>
</tr>
<tr>
<td>450EM</td>
<td>430</td>
<td>-40</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>450EMZ</td>
<td>430</td>
<td>-40</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

*In the table EEMUA and BS 7191 Grades are considered equivalent.

**TABLE 2.1 BS 4360 and BS 7191 STEEL GRADES**
### Table 2.2 ASTM Steels A106

<table>
<thead>
<tr>
<th>Grade</th>
<th>Yield Point N/mm²</th>
<th>Tensile Strength N/mm²</th>
<th>Carbon %</th>
<th>Manganese %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>205</td>
<td>330</td>
<td>0.25</td>
<td>.27 TO 0.93</td>
</tr>
<tr>
<td>B</td>
<td>240</td>
<td>415</td>
<td>0.30</td>
<td>.29 TO 1.06</td>
</tr>
<tr>
<td>C</td>
<td>275</td>
<td>485</td>
<td>0.35</td>
<td>.29 TO 1.06</td>
</tr>
</tbody>
</table>

### Table 2.3 ASTM Steels A333

<table>
<thead>
<tr>
<th>Grade</th>
<th>Yield Point N/mm²</th>
<th>Tensile Strength N/mm²</th>
<th>Carbon %</th>
<th>Test Temp °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>205</td>
<td>380</td>
<td>0.30</td>
<td>-45</td>
</tr>
<tr>
<td>3</td>
<td>240</td>
<td>450</td>
<td>0.19</td>
<td>-100</td>
</tr>
<tr>
<td>4</td>
<td>240</td>
<td>415</td>
<td>0.12</td>
<td>-100</td>
</tr>
<tr>
<td>6</td>
<td>240</td>
<td>415</td>
<td>0.30</td>
<td>-45</td>
</tr>
<tr>
<td>7</td>
<td>240</td>
<td>450</td>
<td>0.19</td>
<td>-75</td>
</tr>
<tr>
<td>8</td>
<td>515</td>
<td>690</td>
<td>0.13</td>
<td>-200</td>
</tr>
<tr>
<td>9</td>
<td>315</td>
<td>435</td>
<td>0.20</td>
<td>-75</td>
</tr>
<tr>
<td>10</td>
<td>450</td>
<td>550</td>
<td>0.20</td>
<td>-60</td>
</tr>
</tbody>
</table>

### Table 2.4 Profiled Sheet Material Standards

<table>
<thead>
<tr>
<th>Material</th>
<th>British Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot dip zinc coated sheet steel</td>
<td>BS 2989</td>
</tr>
<tr>
<td>Hot dip Al/Zn coated sheet steel</td>
<td>BS 6830</td>
</tr>
<tr>
<td>Hot dip zinc coated corrugated profiles</td>
<td>BS 3083</td>
</tr>
<tr>
<td>Hot dip organic coated sheet steel</td>
<td>BS 6781</td>
</tr>
<tr>
<td>Stainless steel sheet</td>
<td>BS 1449</td>
</tr>
</tbody>
</table>

Cold-formed stainless steel sheeting may be specified according to ASTM A666-72.
<table>
<thead>
<tr>
<th>Range</th>
<th>( \sigma_a(\theta) = )</th>
<th>( \bar{E}_{a(\theta)} = )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I elastic</td>
<td>( \bar{E}<em>{a(\theta)} \epsilon</em>{a(\theta)} )</td>
<td>( \bar{E}_{a(\theta)} )</td>
</tr>
<tr>
<td>II transit elliptical</td>
<td>( \frac{b}{a} \sqrt{a^2 - (\epsilon_{a\max(\theta)} - \epsilon_{a(\theta)})^2} + \sigma_{a pr(\theta)} - c )</td>
<td>( \frac{b (\epsilon_{a\max(\theta)} - \epsilon_{a(\theta)})}{a \sqrt{a^2 - (\epsilon_{a\theta} - \epsilon_{a\max(\theta)})^2}} )</td>
</tr>
<tr>
<td></td>
<td>with ( a^2 = \frac{\bar{E}<em>{a(\theta)} (\epsilon</em>{a\max(\theta)} - \epsilon_{a pr(\theta)})^2 + c (\epsilon_{a\max(\theta)} - \epsilon_{a pr(\theta)})}{\bar{E}_{a(\theta)}} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( b^2 = \bar{E}<em>{a(\theta)} (\epsilon</em>{a\max(\theta)} - \epsilon_{a pr(\theta)}) \cdot c + c^2 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( c = \frac{(\sigma_{a\max(\theta)} - \sigma_{a pr(\theta)})^2}{2 (\sigma_{a pr(\theta)} - \sigma_{a\max(\theta)}) + \bar{E}<em>{a(\theta)} (\epsilon</em>{a\max(\theta)} - \epsilon_{a pr(\theta)})} )</td>
<td></td>
</tr>
<tr>
<td>III plastic</td>
<td>( \sigma_{a\max(\theta)} )</td>
<td>0</td>
</tr>
</tbody>
</table>

\( E_{a(\theta)} \) = Initial Young's modulus at temperature \( \theta \)
\( \sigma_{a(\theta)} \) = Stress at temperature \( \theta \)

Table 3.1 FORMULAE STRESS-STRAIN CURVES

(Reference: EC3 PART 10)
(Symbols are defined on Figure 3.3)
<table>
<thead>
<tr>
<th>Steel Temperature °C</th>
<th>Young's Modulus Ratio</th>
<th>Yield Stress Ratio (0.2% Proof Stress)</th>
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</thead>
<tbody>
<tr>
<td>20</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>100</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>200</td>
<td>0.90</td>
<td>0.807</td>
</tr>
<tr>
<td>300</td>
<td>0.80</td>
<td>0.613</td>
</tr>
<tr>
<td>400</td>
<td>0.70</td>
<td>0.42</td>
</tr>
<tr>
<td>500</td>
<td>0.60</td>
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<tr>
<td>1200</td>
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</table>

**TABLE 3.2** STRENGTH AND FLEXIBILITY OF CARBON STEEL AT ELEVATED TEMPERATURES (Source EC4 Part 10, Draft Version)
### Table 3.3. Temperature Modification for Different Heating Rates

<table>
<thead>
<tr>
<th>Heating Rate °C/min</th>
<th>Temperature Modification °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>-15</td>
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<tr>
<td>5</td>
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</tr>
<tr>
<td>2.5</td>
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### Table 3.4 Thermal Properties of Stainless Steel

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>Thermal Expansion x10^{-5}/°C</th>
<th>Thermal Conductivity W/m°C</th>
<th>Specific Heat J/kg°C</th>
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<tbody>
<tr>
<td>20</td>
<td>1.60</td>
<td>14.3</td>
<td>499</td>
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<tr>
<td>100</td>
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<td>499</td>
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<tr>
<td>200</td>
<td>1.66</td>
<td>17.0</td>
<td>510</td>
</tr>
<tr>
<td>300</td>
<td>1.72</td>
<td>18.4</td>
<td>522</td>
</tr>
<tr>
<td>400</td>
<td>1.77</td>
<td>20.0</td>
<td>533</td>
</tr>
<tr>
<td>500</td>
<td>1.83</td>
<td>21.5</td>
<td>544</td>
</tr>
<tr>
<td>600</td>
<td>1.87</td>
<td>23.0</td>
<td>553</td>
</tr>
<tr>
<td>700</td>
<td>1.91</td>
<td>24.5</td>
<td>560</td>
</tr>
<tr>
<td>800</td>
<td>1.93</td>
<td>26.0</td>
<td>563</td>
</tr>
</tbody>
</table>
Fig 3.1 Typical Stress-Strain Curve for Mild Steel and Stainless Steel
Fig 3.2  ANISOTHERMAL CREEP CURVES

Heating rate = 20 °C/min
Applied stress = 350, 300, 250, 200, 150 N/mm²

For Steel Code No. RS138
Fig 3.3  EC3: PART 10 - IDEALIZATION OF STRESS-STRAIN CURVE AT A PARTICULAR TEMPERATURE
Fig 3.5  COMPARISON OF STEEL PROPERTIES AT ELEVATED TEMPERATURES FOR BS5950 : PT 8 AND EC3 : PT 10 STEELS
Fig 3.6 THERMAL ELONGATION AT ELEVATED TEMPERATURES
FIG 3.7 VARIATION OF SPECIFIC HEAT OF CARBON STEEL WITH TEMPERATURE
Fig 3.8  VARIATION OF THERMAL CONDUCTIVITY OF LOW CARBON STEEL WITH TEMPERATURE
Fig 3.9  VARIATION OF STRENGTH WITH TEMPERATURE FOR RQT 501 (BRITISH STEEL PLC) STEELS (0.2% PROOF STRESS)
Fig 3.10  COMPARISON OF LOSS OF STRENGTH VERSUS TEMPERATURE FOR 'BISALLOY 80' (BHP) STEEL AND EC3 : PART 10 (0.5% STRAIN)
Fig 3.11
Comparison of Loss of Strength with Temperature of Stainless Steel and Carbon Steel (0.5% Strain)
Fig 3.12  Loss of Strength at Elevated Temperatures for a Variety of Stainless Steels (1.0% Minimum Proof Stress)
Fig 3.13  Comparison of Loss of Strength with Temperature for BS1501 : Part 1 Grade 223 (490) Steel and EC3 : Part 10 (0.2% Proof Stress)
Fig 3.14 Comparison of Loss of Strength with Temperature for Two BS1501 Pt 2 Steels and EC3: Pt 10 (0.2% Proof Stress)
Fig 3.15  ELEVATED TEMPERATURE STRESS STRAIN CURVES FOR NIPPON STEEL SM50A-NFR

$F_y = 354 \text{N/mm}^2$
Fig 3.16   Comparison of Loss of Strength at Elevated Temperatures for Nippon SM40-NFR Steel and a Typical Low Carbon Steel (0.2% Proof Stress)
Fig 3.17 Comparison of Loss of Strength with Temperature for BS1501 Part 2 Grade 271 'Ducol W30' Steel and EC3 Part 10 (0.2% Proof Stress)
Fig 3.18 Strength of Bolts and Welds (BS5950 : Part 8) at Elevated Temperatures
Fig 4.1
Stress vs Strain: British Steel Data Range 20°C - 600°C

- 20°C
- 500°C
- 600°C

Stress N/mm²

Strain %

0 0.2% 0.4% 0.6% 0.8% 1% 1.2% 1.4% 1.6% 1.8%
Fig 4.2  Stress vs Strain : British Steel Data Range 650°C - 900°C
Fig 4.3  Comparison of British Steel and EC3 Data at 200, 400 & 600 Degree C
GLOSSARY

Anisothermal Test: A tensile test for obtaining the properties of steel at elevated temperatures whereby the sample is first loaded to a prescribed level and then heated at a specific rate until the sample fails. Developed specifically for use in fire-resistant calculations as the test most largely resembles the physical behaviour of steel in real fires.

API 5L: The American Petroleum Institute's Grade 5L steel, often used to specify the standard of tubular structural elements. BS 4360 Grade 50 equivalent.

API 5B: A lower grade than API 5L. A BS 4360 Grade 43 equivalent.

BS 4360: The British Standard for hot-rolled structural steels, often used in the specification of offshore structural steels.

Caisson: A vertically aligned pipe, running from the module deck to a sub-sea level, forming a service line for seawater suction or sewage/drilling disposal.

Chemical Composition: The proportion by weight of constituent elements in a particular batch of steel as determined by ladle analysis.

Conductor: The outer tubing of a drill-string, often of 30 or 24 inches diameter, extending from below the mudline to the drilling deck.

Creep: The time-dependent straining of a material under a constantly applied load, and in the context of this report also at a fixed temperature.

FR Steels: Fire-resistant steels such as British Steel "Ducol" and Nippon SM50A-NFR steel, which have a chemical composition calculated to improve the yield strength at elevated temperatures.

Heating Rate: The rate, measured in deg C per minute, that a steel sample is heated.

Heat Treatment: The modification of the properties of steel by the controlled application of heating during or after the manufacturing process.

Isothermal Test: A test method for obtaining the properties of steel at elevated temperatures. Tensile tests are performed on samples which are heated and are then maintained at a constant temperature whilst a steadily increasing load is applied to the sample.
An alloy of copper, nickel and iron which is used extensively in the manufacture of firewater mains and fittings; distinguished by its characteristic bronze appearance. Some authors use the spelling Cunifer.

Lowest astronomical tide. A level of the sea surface used on offshore structures to reference the elevation of decks, etc.

The steelmaking process as selected by the manufacturer in order to produce a particular steel grade.

The intersection point of bracings on a structure; the sub-assembly of node body (barrel in tubular joints), bracing stubs and stiffeners located at such a point.

The stress at which the strain of a material reaches a particular value, for example the 0.2% proof stress. Proof stress is a valuable concept in materials which do not exhibit a sharp yield point. When considering elevated temperature behaviour of steels which are in common usage in the fabrication of offshore structures the concept of Proof Stress is particularly important because low carbon steels do not have a sharply defined yield point at higher temperatures.

An acronym for Roller Quenched and Tempered steels. These steels are subjected to a special manufacturing process which enhances the grade strength normally associated with the chemical composition of the batch.

(Also work hardening); the tendency of an elastic-plastic material to exhibit increased resistance to high strains.

The ratio of heated perimeter ($H_p$) to the cross-sectional steel area ($A$).

The amount of heat, measured in Joules, required to raise one kilogram of a substance by one degree c. This term is included herein for ease of reference although a more detailed definition may be found elsewhere.

A correction applied to the temperature of effective yield of a steel sample to account for the interaction of creep and heating rate.

The stress at which a steel sample departs from linear elastic behaviour to plastic deformation in a standard tensile test.

For materials which exhibit no clear yield point - such as mild steels at elevated temperatures, the stress corresponding to a particular strain, often 0.2%. See also Proof Stress.
List of Tables

<table>
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<th>Table</th>
</tr>
</thead>
<tbody>
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</tr>
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</tr>
<tr>
<td>B3</td>
</tr>
<tr>
<td>B4</td>
</tr>
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<td>STRESS N/mm² (MPa)</td>
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UNIT OF MEASUREMENT AND CONVERSION FACTORS

TABLE B1 STRESS CONVERSIONS

1 bar (14.7 lbs per inch²) is approximately equal to 100 kN/m²
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<th>TEMPERATURE in Deg C</th>
<th>TEMPERATURE in Deg F</th>
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<td>1530</td>
<td>2766</td>
<td>Iron Melts</td>
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**TABLE B2  TEMPERATURE CONVERSIONS**
Thermal Expansion

The units of thermal expansion are strain per deg temperature rise and hence the dimensions of the quantity are "per degree".

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<tr>
<th>Expansion per Deg Celsius</th>
<th>Expansion per degree Fahrenheit</th>
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</tr>
<tr>
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**TABLE B3 CONVERSION OF THERMAL EXPANSION**

Specific Heat

Specific Heat is the amount of heat required to raise one unit mass of a specific substance by one unit of temperature. It is measured in Joules per kilogram in SI units and in British Thermal Units per pound (BTU/lb) in the Imperial system.

<table>
<thead>
<tr>
<th>SPECIFIC HEAT in JOULES/KG</th>
<th>SPECIFIC HEAT IN BTU/LB</th>
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<tr>
<td>1.000</td>
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**TABLE B4 SPECIFIC HEAT CONVERSIONS**
BLAST AND FIRE ENGINEERING FOR TOPSIDE STRUCTURES
WORK PACKAGES (WP)

WP No: FR1

WP TITLE: Experimental data relating to the performance of steel components at elevated temperatures

WP START DATE: Month 1
WP END DATE: Month 6 and Month 9
DURATION: 9 Months

OBJECTIVES:

To identify what available experimental knowledge can be used by the offshore industry in the assessment of the performance of steel components at elevated temperatures.

To identify gaps in present knowledge.

DESCRIPTION OF WORK:

The work package will collate and assess experimental information relating to the influence of temperature on both material properties and the response of structural components, protected or unprotected. A full assessment will be made of the type of components tested, test regimes, restraints, stress and deflection levels and reported results. Data will be collated from both protected and unprotected steel and permission sought from organisations to release confidential data.

INPUT TO ACTIVITY:

Literature searches and direct communications with investigators, operators, steel manufacturers and bodies such as the European Steel and Coal Community.

DELIVERABLES:

A detailed report on the findings with particular reference to the applicability of collated data to the offshore design problem.

Requirements for future work.