Guide to Site Welding

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FOREWORD

This publication has been prepared to fill what appears to be a gap in the range of knowledge on welding of a typical structural engineer. Welding has always been a topic where there appears to be only two levels of competence; either very high, or very low. This guide is directed at those with a limited understanding of the issues of site welding, and should be considered as a supplement to other SCI publications that provide the basic levels of knowledge and understanding.

Although the scope of the guide covers site welding, information of a more general nature that is common to both site and shop welding has been included where this will aid understanding.

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SUMMARY

This publication offers guidance to structural engineers considering, specifying and checking site welding. Its purpose is to create a better understanding and confidence in site welding, and to provide sufficient information to enable non-specialist structural engineers to manage site welding successfully.

Many features of site welding common to both shop and site welding are covered in sufficient detail to provide background to the site-specific guidance. Site practice for cutting and welding both new and existing material on site is described, together with advice on the issues to be considered prior to specifying site welding. Although the structural engineer is unlikely to be directly responsible for certain activities, such as preparing welding procedure specifications, activities outside the structural designer’s responsibility are described in order to cover the subject comprehensively.

This publication includes sections on: welding structural steel and other materials, site practices and procedures, designing for site welding, quality assurance and weld testing.

The publication does not replace expert welding advice. Qualified welding engineers should be consulted for specific advice in situations outside the scope of this publication.

Guide de soudage sur chantier

Résumé

Cette publication donne une guidance destinée aux ingénieurs devant s’occuper des spécifications et du contrôle de soudures réalisées sur chantier. Son objectif est de créer une meilleure compréhension et une meilleure confiance au soudage sur site et de fournir une information suffisante pour permettre aux ingénieurs non spécialisés en soudage de gérer de manière satisfaisante l’activité de soudage sur chantier.

Différents aspects, qui sont communs au soudage en atelier et au soudage sur chantier, sont couverts avec suffisamment de détail pour fournir une connaissance suffisante à une guidance spécifique au soudage sur chantier. Les pratiques de chantier relatives à la découpe et au soudage sur chantier, de matériaux neufs ou existants, sont décrites. Bien que l’ingénieur de structure n’est généralement pas responsable de certaines activités, comme la préparation de spécifications relatives aux procédures de soudage, des activités de ce type sont décrites afin de couvrir l’ensemble du sujet.

Le guide comporte des chapitres consacrés : au soudage d’aciers structuraux et d’autres matériaux, aux pratiques et procédures de chantier, au dimensionnement des soudures réalisées sur chantier, à l’assurance qualité et aux essais et vérifications des soudures.

Cette publication n’a pas la prétention de remplacer les conseils d’un expert en soudure. Ces derniers doivent être consultés pour des conseils spécifiques dans le cas de situations qui sortent du cadre de ce guide.
Anleitung zum Baustellenschweißen

Zusammenfassung

Diese Publikation bietet eine Anleitung für Tragwerksplaner, die das Schweißen auf der Baustelle in Erwägung ziehen, angeben oder überprüfen. Ihr Zweck ist es, besseres Verständnis und Vertrauen beim Baustellenschweißen zu erzeugen, und genügend Informationen zu besorgen, um nicht spezialisierten Tragwerksplanern zu ermöglichen, mit dem Baustellenschweißen erfolgreich umzugehen.

Viele Merkmale des Baustellenschweißens, die sowohl in der Werkstatt als auch auf der Baustelle anzutreffen sind, werden genügend genau erläutert, um für die baustellenspezifische Anleitung Hintergrundinformation zu besorgen. Praktisches Vorgehen zum Ablängen und Schweißen von neuem und bestehendem Material auf der Baustelle wird beschrieben, zusammen mit Ratschlägen zu Fragen die berücksichtigt werden müssen bevor auf der Baustelle geschweißt wird. Obwohl es unwahrscheinlich ist, daß der Tragwerksplaner direkt verantwortlich ist für gewisse Aktivitäten wie z.B. Schweißanweisungen, werden solche Aktivitäten beschrieben um das Thema umfassend darzustellen.


Die Publikation ersetzt Expertenratschläge beim Schweißen nicht. Qualifizierte Schweissfachingenieure sollten in Situationen außerhalb des Bereichs dieser Publikation herangezogen werden.

Guía para la soldadura in-situ

Resumen

Esta publicación es una guía para ingenieros de estructuras en lo relativo a especificaciones y control de soldaduras in-situ. Su propósito es la creación de una mejor comprensión y confianza en la soldadura a pie de obra y en el suministro de información suficiente para ayudar al ingeniero no especializado en la dirección de las soldaduras in-situ.

Se cubren muchas características de la soldadura comunes tanto en las de fábrica como en las de pie de obra, con suficiente detalle para crear la experiencia necesaria. También se trata la práctica in-situ para corte y soldadura de material existente o nuevo, junto con consejos sobre los temas considerados prioritarios en las especificaciones. Aunque no es probable que el ingeniero estructuralista sea responsable directo de ciertas actividades como la preparación de especificaciones para los procesos de soldadura, se describen para tener un tratamiento completo del tema.

La publicación incluye secciones sobre: soldadura de acero estructural y otros materiales, procedimientos y prácticas in-situ, proyecto de soldaduras a pie de obra, aseguramiento de la calidad y ensayos de soldaduras.

La publicación no sustituye el consejo de los expertos que deben ser consultados en situaciones especiales que caigan fuera del alcance de aquélla.
Guida alle saldature in opera

Sommario

Questa pubblicazione è una guida per gli ingegneri strutturisti per la valutazione, le specifiche ed il controllo delle saldature in cantiere. Lo scopo del volume è di contribuire ad una migliore comprensione e conoscenza delle saldature in opera, fornendo anche sufficienti informazioni per rendere possibile una soddisfacente trattazione di questo argomento anche ai non esperti.

Molte caratteristiche delle saldature in opera, comuni comunque anche alle saldature in stabilimento, sono affrontate con un adeguato livello di accuratezza in modo da fornire un soddisfacente livello di conoscenza sull’argomento. Vengono descritte le corrette pratiche di cantiere per taglio e saldatura su elementi sia nuovi che già utilizzati, unitamente a consigli sull’analisi da effettuare precedentemente alla definizione delle specifiche sulle saldature. Nonostante l’ingegnere strutturista sia raramente responsabile per alcune attività, come la preparazione delle specifiche di saldatura, vengono descritte anche attività non coperte dalla responsabilità del progettista strutturale in modo da consentire un’esauriente trattazione della tematica.

Questa pubblicazione include capitoli sulla saldatura di acciai strutturali ed altri materiali, pratica e procedure di cantiere, progettazione di saldature in opera, assicurazione di qualità e sperimentazione sulle saldature.

La pubblicazione non sostituisce i consigli basati sull’esperienza. Gli ingegneri con esperienza nel campo delle saldature dovrebbero essere consultati per tutte quelle specifiche situazioni non trattate nel volume.
1 INTRODUCTION

1.1 The use of welding in construction
Welding is a very simple and ancient process for the joining of two pieces of metal. It relies on the crude concept of melting the ends of the two pieces, then allowing the common weld pool to freeze to produce one continuous element.

Many issues need to be considered in taking the crude concept and ensuring that welds for structural purposes possess the required strength and are free from defects. Welding of structural steelwork is not as difficult or as complicated as some would suggest. Yet, while welding is commonplace in other industries, it does not find widespread use in the structural and civil engineering sectors, particularly on site. The most extreme example of this is the almost total absence of site welding on steel building projects; to the eye of the welding engineer, these are one of the most straightforward applications of welding.

The reasons for avoiding structural welding may have been valid many years ago when welding was considered a ‘black art’, with a history of inexplicable failures, but these are no longer valid arguments. Research and development have advanced the understanding of welding technology considerably since welding began to be used in structural applications at the start of the twentieth century. It is now entirely reasonable for the designer to expect that structural welds made on site will match the quality of those fabricated in the workshop.

Site welding should be considered as a reliable procedure to be specified with confidence, rather than being a technique to be avoided, if possible. Welding on site can be advantageous in a number of circumstances (See Section 6.1), and structural designers should consider welding to be within the range of normal site operations.

1.2 Scope of this publication
The purpose of this publication is to emphasise the important message that structural welding may be specified and undertaken with confidence, and to guide structural engineers on the ways to ensure that good quality welding can be achieved, even on site. The guide contains the information necessary for non-specialist engineers to determine the critical factors in the welding process and to judge the areas that need special attention. In most cases, the structural engineer’s role will be to ensure that the proposed processes, procedures and competence levels are all appropriate for the joints being completed. In some circumstances the structural engineer will be able to modify the design to simplify the welding activity, or to improve the cost-effectiveness of the welding operations. A glossary of welding terms is included in Appendix A.

It is assumed that the reader has a basic familiarity with welding (especially of structural steels), but if this is not the case, other publications, such as *Introduction to the welding of structural steelwork*[^1] and *Structural steelwork welding handbook*[^2] can help.

A Bibliography of other helpful references is included in Appendix B.
Section 2 provides a summary of the particular processes that are most likely to be used on site. Section 3 discusses the Standards that cover the welding of structural steelwork, and demonstrates by example the process by which an appropriate welding procedure specification is developed. Section 4 describes the welding of other materials commonly found on site. Section 5 highlights the important additional considerations that must be considered when undertaking site welding. These concern not so much the welding process itself, but the necessary provisions for access, protection and appropriate provisions in the construction programme. Section 6 illustrates practical details for joints and associated temporary support that are commonly adopted when site welding. Section 7 reminds the reader that the quality of site welds should be no less than those completed in the workshop, and discusses the specifications for testing and inspection of welds. Section 8 describes the processes used to inspect completed welds.

A word of caution: this guide cannot replace the need, on many occasions, for the advice of an expert welding engineer. Welding can be a technically complex process, and bad welding is certainly worse than no welding at all. Welding expertise is readily available and it is not uncommon for steelwork contractors, general contractors and consultancy practices to have appropriately qualified welding engineers. Within the UK, TWI (formerly known as The Welding Institute) operates a registration scheme for welding engineers, and may be contacted for verification of the qualifications of specific individuals whose advice is being relied upon. Contact details for TWI are given in Appendix C.

1.3 Structural steels

By far the biggest production of steel is represented by the family known as the carbon-manganese range of steels. These steels, as the name suggests, are a simple alloy of iron, carbon and manganese. The steels in this range are used for practically all building and bridge structures, ships and offshore structures, and as steel bars for reinforced concrete.

Carbon-manganese steels are probably the easiest of steels to weld both on site and in the fabrication shop. These steels in their plate or sectional forms are specified in published Standards, such as BS EN 10025[3] and BS EN 10113[4] for rolled sections and plates. Hot finished structural hollow sections are specified to BS EN 10210[5].

The site welding practices for these structural steels are essentially the same as shop fabrication practices, but some additional precautions must be taken, for example to protect against the detrimental effect of the weather or the site environment, in order to ensure that site welding is as reliable as welding in the fabrication workshop.

1.4 Site welding and safety

As with any site operation, safety must be a primary consideration. The Health and Safety Executive have identified that 40% of serious injuries on construction sites result from falls, while 5% are from electricity. Site welding can involve both of these hazards and therefore the need for attention to detail with regard to safety is obvious. The Construction (Design and Management)
Regulations 1994 Brief\textsuperscript{[6]} require construction industry professionals to identify potentially hazardous operations and devise ways of addressing them.

It should also be noted that much site welding takes place when structures are partially complete, or whilst temporary works support the structure. Structures can be more vulnerable in these stages because of their partial completion, the lesser quality of the (temporary) works, or unexpected loading patterns. Site welding is therefore likely to be one of the key activities during the construction process that structural engineers must consider in their risk assessments.

1.5 The achievement of quality

Welding quality, and thus reliability, cannot be relaxed simply because the operation is carried out on site. Suitable standards and procedures need to be established long before any work is carried out, and must be adhered to. There should be no exceptions to this. Although large structural connections will often attract a lot of attention and engineering effort, there is also a need for every site welding operation, no matter how small or apparently innocuous, to be monitored and controlled.
2 WELDING AND CUTTING PROCESSES

2.1 Welding processes for structural steelwork

The following processes are commonly used in the welding of structural steelwork:

- Manual Metal Arc (MMA)
- Metal Inert Gas (MIG)
- Metal Active Gas (MAG)
- Flux Cored Arc Welding (FCAW)
- Submerged Arc Welding (SAW)
- Tungsten Inert Gas Welding (TIG)

Note that only the shielding gas differs in the MIG and MAG processes. Colloquial reference to either process may be by either MIG or MAG, or “CO\textsubscript{2} welding”, referring to one of the shielding gasses commonly used. Details of each process may be found in numerous reference works. The processes most suited to site activity are described in more detail in the next section.

2.2 Welding processes for site use

Although it is possible to transfer any of the welding processes described in Section 2.1 to site, some are more amenable to use on site than others.

The factors that need to be considered when choosing a process for use on site include:

1. The portability of the equipment. This applies to both the equipment at the work place and the power sources. Access to each workplace, and the necessary movement of the equipment around the structure, must be considered.

2. Power requirements. Conventional generators or transformers, designed for use on site, can provide electrical power. Processes that require highly specialised equipment to provide the power source should be avoided.

3. Shelter from wind. Site work is frequently exposed to draughts or wind, which may disrupt the arc shielding. Unless shelter is provided, welding processes that are less sensitive to disruption by wind are preferable.

4. Positional welding. In a workshop environment, the work piece can usually be turned to allow the welding to be completed in a convenient position (i.e. ‘downhand’, with the weld pool below the consumable). On site, the weld orientation is usually fixed, frequently necessitating welding in the more difficult ‘overhead’ positions, where the weld pool is above the consumable. Some processes are more flexible for a variety of positional welds, and these would be preferred in most circumstances.

5. Humidity. Weld processes differ in the hydrogen levels that result in the finished weld. A process which is less sensitive to the generally damp atmosphere found on site, and which will therefore produce lower hydrogen levels in the weld, would be preferred.
6. Variation of welded joints. Site welding may well involve a range of joint types, material thickness etc., which would normally demand different selections of consumable, welding parameters and welding technique. Processes and equipment, which allow such versatility on site, are generally preferable, unless the welding comprises large numbers of identical joints, where a less versatile, but more efficient process would be advantageous.

Although no single welding process can satisfy all of these criteria, two welding processes stand out as clear favourites when site welding. These are Manual Metal Arc (MMA) welding, and gasless Flux Cored Arc Welding (FCAW). These two processes are described briefly in the following Sections.

2.3 Manual metal arc welding

The Manual Metal Arc (MMA) welding process, often called ‘stick welding’, is the most common of the various arc welding processes used on site. MMA is versatile and uses relatively simple equipment. MMA is used extensively in industrial fabrication and structural steel erection.

In Manual Metal Arc welding an arc is struck between the work piece and a flux covered wire electrode. The electrode (which may be 300 to 350 mm long initially) is held in an electrode holder and is connected to the power source by a cable. The electrical circuit is completed by another cable connecting the work piece to the other pole of the generator or power source. The electrical arc provides the energy to melt the end of the consumable electrode (which is consumed during the welding process), and also provides the force to transfer the molten metal into the weld pool. The arc also melts and vaporises the flux covering to the electrode, which provides arc shielding and protection to the solidifying weld pool. Figure 2.1 illustrates MMA welding.

![MMA Welding Diagram](image)

**Figure 2.1** MMA welding

The skill of the welder comes in manipulating the tip of the electrode over the weld pool and progressing into the unfused portion of the joint, such that the heat of the arc melts both the parent metal and the electrode core in a controlled manner. The welder must control the arc length to the order of 0.7 mm to 1.5 mm while at the same time the electrode is continuously being consumed, becoming shorter and shorter in length. Eventually, the stub becomes so short that welding has to be stopped in order to replace the electrode; this is the major aspect that affects the productivity of the process. (Note: the amount of
weld deposited per electrode is called the ‘run out length’ and can be used as a measure of the heat input of the weld from tables in BS EN 1011-2[8].

The versatility of the MMA welding process is enhanced by the ability of the electrode manufacturer to offer a range of the composition/chemistry of the flux and electrode wire. Metallic particles may be included in the flux covering to increase deposition rates and/or to include alloying elements in the weld pool to make the weld stronger tougher and more resistant to corrosion, etc.

Additionally, the characteristics of the arc and penetration of the weld can be adjusted by altering the coating, current, voltage and polarity (electrode DC positive or negative, or AC). These factors control: the shape of the weld bead, the depth of penetration, deposition rates etc.

The equipment used in the MMA process can accommodate the range of electrodes available. As the electrodes are relatively inexpensive, the process is both economic and versatile. The flux surrounding the electrode can absorb moisture, leading to increased levels of (unwelcome) hydrogen in the completed weld. This may be overcome by baking the electrodes prior to use and by keeping baked electrodes in heated “quivers” until they are required.

The power sources for MMA welding are relatively small, robust and easily portable around the structure. As no shielding gas is required, the welding equipment is simple, and easy to set up. The simplicity of the process equipment and versatility arising from the choice of different electrodes make MMA the most common process for site welding.

### 2.4 Flux cored arc welding

Whilst MIG/MAG welding is popular in fabrication workshops, the requirement to have gas supplies on site, and the susceptibility of the process to disturbance from wind, mean the process is only occasionally used on site.

The Flux Cored Arc Welding (FCAW) process is essentially similar to MIG/MAG welding, but without the need for a protective gas shield. FCAW uses a continuously fed consumable wire to a welding gun held by the operator. The wire consumable has an internal core containing flux, and other alloying elements if required. The FCAW process combines the versatile character of Manual Metal Arc welding (a range of consumable compositions and flux cores are available) and the productivity of metal inert gas (MIG) welding, since the process need not be stopped to replace electrodes.

The advantages of the FCAW process are:

1. An increase in productivity compared with MMA, since the process does not need to be halted whilst electrodes are replaced.
2. Compared to MMA, the equipment allows much higher currents to be used and therefore higher deposition rates can be achieved.
3. The electrical control provides a self regulating arc, by automatically adjusting the speed of the wire feed. This means that the need for the welder to maintain an arc length of 0.7 mm to 1.5 mm by manual control is effectively removed.
4. Since the flux is inside the steel tube, much less moisture from the atmosphere is absorbed, and thus there is much less likelihood of hydrogen contamination of the weld.

5. The higher heat inputs and better control of diffusible hydrogen lead to a reduced need for preheat.

6. The relatively short electrode allows better access into restricted areas.

7. The process is self-shielding, and as such is much less sensitive to draughts than MMA, where the arc can be disturbed.

8. The high deposition rate and good penetration which characterise FCAW means the process can accommodate less precise fit-up of the parts to be joined.

Figure 2.2 shows the basic equipment.

![Diagram of flux cored arc welding](image)

**Figure 2.2  Flux cored arc welding**

The power sources and equipment required for FCAW are more expensive than that for MMA, and considered less robust, with complex electrical control and mechanical wire feed. Portability around the site is less convenient than MMA welding. However, advances in power systems technology are leading to simple, robust equipment more suited to work on site.

### 2.5 Cutting on site

The need to modify steelwork on site is a common requirement, particularly in refurbishment projects, or during extensions to existing structures. Whereas new fabricated elements should arrive on site without further need for modification, site cutting may be required to remove existing steelwork, or to prepare existing steelwork for the addition of new members, or to modify existing members, for example, by cutting holes for services.

Mechanical cutting with saws, grinders, tank cutters or stitch drilling may be used, but thermal cutting does offer advantages in cost and speed. There are two main thermal cutting processes employed on site, flame cutting and plasma cutting, described in the following Sections. Both processes must be managed, to ensure they are carried out safely and by competent personnel.
2.5.1 Flame cutting

Flame cutting relies on a fuel gas burning with oxygen to heat the steel to its ignition temperature. The steel itself then burns in a second stream of oxygen. The oxidised iron is blown out by the high velocity gas jet to produce the cut, giving a controlled and precise burning through the steel. The equipment can cut a range of thickness of steel, in a clean and economical manner.

Energy costs for the flame cutting process are relatively low. The fuel gases commonly used are either acetylene or propane. For site use, propane is preferred as it gives a quicker, cleaner, cut and is also safer. Acetylene is an unstable gas; acetylene and copper together form copper acetylate which is an impact explosive. Propane, on the other hand, has only the obvious hazards of any bottled combustible gas. The cylinders, although bulky, are portable.

Figure 2.3 illustrates the process.

Due to the burning nature of the process, it is essential that the metal oxide formed on the surfaces of the cut should melt at a lower temperature than the base material. Otherwise, a refractory oxide layer forms over the surface and protects the metal, terminating the reaction. Oxides of carbon-manganese steels do have a lower melting point than the steel itself, making the process suitable for common structural steels. Oxides of stainless steel have a high melting point and therefore ordinary flame cutting is not immediately appropriate. It is possible to cut stainless steel by adding iron powder to sustain the reaction, but this technique is slow, costly and dirty.

Expert advice should be sought on the need to grind the cut surface prior to subsequent welding. Flame cutting can lead to hardening of the cut surface, and the surface may need to be ground clean before any subsequent welding. Failure to clean the cut surface may lead to defective welds through either lack of side wall fusion or slag inclusions. If the surface has been machine flame cut, specifications for bridge works[^7] do not insist that the surface should be ground if it is to be incorporated into a weld.

If in doubt, the general rule is to ensure the cut surface is prepared before welding by grinding.
2.5.2 Plasma cutting

Plasma cutting is a faster process than flame cutting, avoids oxide formation on metals such as stainless steel, and does not produce the hazardous gases associated with flame cutting. Plasma cutting has three important characteristics:

1. The process temperature is high enough to melt the metal and all oxides.
2. The concentrated energy density is sufficient to melt a narrow, well-defined kerf (the gap resulting from the cutting process).
3. There is adequate momentum to remove the molten metal.

A diagrammatic section of plasma cutting torch is shown in Figure 2.4

![Plasma cutting torch diagram](https://via.placeholder.com/150)

**Figure 2.4 Plasma cutting torch**

The plasma arc is struck between the electrode (which is not consumed) and the work piece, with a shielding gas flowing through the nozzle around the plasma stream. This process can be used for welding, and is known as Tungsten Inert Gas (TIG) welding, (the electrode is primarily tungsten). However, at higher arc currents and increased gas flows, the same process is used for cutting and results in fast, clean cuts.

Plasma cutting may be used in a workshop environment for most metals up to 100 mm thick at speeds much greater than other thermal or mechanical methods. Major advances in cutting torch design and reliability have led to the introduction of compact, lightweight cutting systems for hand cutting of materials up to 20 mm thick, and are suitable for use on site. These units use air for the plasma gas and for torch cooling. Further developments have included the incorporation of compressor units in the equipment which means that no gas/air supplies, either piped or bottled, are needed, only an electrical power supply.

The economy of operation, and the ability to cut a wide range of otherwise 'difficult' materials (stainless, aluminium, copper, brass, etc.) with an attractive combination of speed and quality, mean that plasma cutting is likely to become an increasingly common process on site. Specialists should be consulted as to the latest equipment and thickness that may be cut with site equipment.
3 WELDING STRUCTURAL STEEL

3.1 Specifications and practices
All welding of constructional steelwork, both in the fabrication workshop and on site, should follow the guidance of Parts 1 and 2 of BS EN 1011 *Welding - Recommendations for welding of metallic materials*.[8]

BS EN 1011 contains a great deal of sound advice and is an excellent source of guidance - readers are encouraged to obtain a copy of Part 2 of the Standard, which covers arc welding of ferritic steels.

In Annex A of BS EN 1011-1, there is a “summary of information to be supplied by the purchaser”. This list is a useful guide to the designer, of the matters that need to be addressed, for both shop and site welding. The matters listed are:

- the application standard to be used together with any supplementary requirements
- the specification of welding procedures, non-destructive testing procedures and heat treatment procedures
- location of all the welds
- welds which are to be made in the workshop, or elsewhere
- the approach to be used for welding procedure approval
- whether approved welders are required
- selection, identification and/or traceability, e.g. for materials, welders and welds
- surface finish and weld profile
- quality and acceptance requirements for welds
- handling of non-conformities, e.g. correction of faulty welds or distortion.

This Section of the guide looks at key aspects in the above list and provides a basic introduction for readers who are less acquainted with the formalities associated with welding practices.

3.2 Application standards
In BS 5950-2[9] and BS 5400-6[10], the principal structural Standards for the use of steelwork in buildings and in bridges respectively, reference is made to the BS 5135. The matters in BS 5135 thus become part of the contractual application Standard for construction. However, BS 5135 has been withdrawn and replaced by BS EN 1011. Future amendments of both structural Standards will need to make reference to BS EN 1011. In addition to referencing BS 5135, the structural Standards also require that welding procedure specifications comply with BS EN 288-1, -2 and -3[11], as appropriate.

BS 5950-2 also requires that the welding operatives be qualified to BS EN 287[12], and this is generally also made a requirement in bridge specifications.
3.3 Welding procedure specifications

A welding procedure specification (WPS) describes in detail how a joint will be welded. Welding procedure specifications to BS EN 288 specify the welding consumable, welding parameters (voltage, amperage, travel speed etc.) and detail how the weld will be completed. Weld procedure specifications are qualified, insofar as their applicability is limited to, for example, steels of certain properties, and a maximum combined material thickness. It is important that the weld procedure specification is appropriate for the specific circumstances of the joint being welded.

Every WPS should be related to a weld procedure approval record (WPAR), which confirms the satisfactory welding and testing of a similar test joint. If an approved WPS already exists that is appropriate for the joint to be welded, this may be used for the production welds. If the details of the proposed joint are not covered by an existing WPS, a new WPS must be developed.

The process leading to an approved WPS is:

1. Prepare a preliminary welding procedure specification (pWPS). This will be prepared on the basis of past experience, and propose tentative parameters for the joint.
2. Weld a test piece, following the parameters described in the pWPS, under conditions representing the production welding.
3. Subject the completed test piece to a number of tests to demonstrate a satisfactory result, and prepare a weld procedure approval record (WPAR).
4. Prepare a WPS, based on the welding parameters used in the approval test.

Engineers invited to review or check a WPS for suitability may find the following basic checklist helpful.

- Does the WPS cover the joint type, arrangement, consumables and process to be used?
- Is the WPAR referenced?
- Were the Charpy tests recorded on the WPAR carried out at the appropriate temperature, with a satisfactory result?
- Is the carbon equivalent (CE) of the steel within the range covered by the WPS?
- Is the combined thickness of the joint within the limit covered by the WPS?

Note that a WPS remains valid indefinitely.

Comprehensive guidance on the range of approval permitted following a successful procedure trial (i.e. the range of WPS which may be related to a WPAR), may be found in BS EN 288-3[1].

The drawing up of a WPS requires consideration of the factors relevant to the weld that is to be made – its size, the parent material, the conditions during welding, etc. Guidance on the factors that necessitate the preparation of a new welding procedure specification, or to the choice of an existing welding procedure specification that is suitable for the particular weld is given in BS EN 1011. The recommendations in that Standard are discussed below.
3.4 Recommendations for welding

BS EN 1011-2 contains a number of informative Annexes, making up the bulk of the Standard, which provide excellent guidance on the avoidance of defects in welds. The guidance does not cover welder-induced defects due to poor practice of workmanship, but addresses the key concerns of hydrogen cracking, solidification cracking and lamellar tearing. Of these, hydrogen cracking is the most significant potential defect that is likely to occur if carefully prepared procedures are not followed. The following Sections summarise the guidance in BS EN 1011-2 for the avoidance of hydrogen cracking.

3.4.1 Avoidance of hydrogen cracking

Hydrogen cracking (sometimes known as cold cracking), concerns cracks in the heat-affected zone of the parent metal adjacent to the weld, as shown in Figure 3.1. The cracks themselves result from the presence of hydrogen in the weld. Hydrogen cracking can lead to brittle failure with costly and sometimes tragic results.

![Figure 3.1 Hydrogen cracking in a fillet weld](image)

For hydrogen cracking to occur at all, four conditions must be met simultaneously:

1. There must be sufficient hydrogen.
2. There must be a tensile stress on the weld.
3. The steel must be susceptible to hydrogen cracking.
4. The steel temperature must be less than approximately 150°C.

Conditions 2 and 4 are inevitable. Tensile stresses result as the weld contracts - an effect which is worsened by high degrees of restraint, in for example, a heavily stiffened fabrication. The measures that can be taken to reduce the risk of hydrogen cracking are therefore to control the amount of hydrogen present, taking account of the susceptibility of the steel itself. Control of hydrogen in the weld involves controlling the hydrogen input, and allowing greater opportunity for the hydrogen to diffuse out of the weld.

**Hydrogen content**

The primary source of hydrogen is the consumable, assuming joints are clean and the welding arc has been properly protected from the atmosphere by a flux or gas shield. BS EN 1011-2 describes five hydrogen scales according to the
diffusible hydrogen content from Scale A (more hydrogen) to Scale E (less hydrogen). Using consumables that lead to less diffusible hydrogen will reduce the risk of hydrogen cracking. Unless a low hydrogen Scale is required, it is usual to assume Scale B or C. Welding engineers can advise on appropriate Scales.

**Controlled cooling**

Slower cooling, first allows more time for hydrogen to safely diffuse out of the weld, and second improves the rate of diffusion, since hydrogen solubility increases with temperature. Three factors affect the cooling rate:

1. The heat sink. The extent to which the parent metal acts as a heat sink, is expressed as the “combined thickness”, which is the sum of the element thicknesses, measured at 75 mm from the joint, as shown in Figure 3.2. The greater the combined thickness, the greater the heat sink and the more rapid the cooling. To avoid hydrogen cracking, a slower cooling is preferable.

\[ \text{Combined thickness} = t_1 + t_2 + t_3 \]

![Figure 3.2 Combined thickness](image)

The heat input during welding. The heat input is given by:

\[ \text{heat input} = k \times \frac{U \times I}{v} \times 10^{-3} \text{ (kJ/mm)} \]

where:

- \( k \) is a thermal efficiency factor for the welding process (usually 0.8)
- \( U \) is the arc voltage (volts)
- \( I \) is the arc welding current (amps)
- \( v \) is the welding speed (mm/sec.).

The greater the heat input, the slower the cooling rate.

2. Any pre-heat applied to the joint to raise the initial temperature.

Maintaining higher temperatures for longer periods reduces the cooling rate.

Pre-heat is usually applied on site by oxy-fuel gas heating torches. Electric heating panels are available, though are more suited for use in a workshop environment.

Figure 3.3 shows a column base detail prepared for site welding. The whole connection is surrounded by a lightweight tent arrangement to protect the
operation from dampness and draughts. Preheat is being applied by gas burners placed under the baseplate.

![Image of column base with preheat arrangements](image)

**Figure 3.3** Column base with preheat arrangements

The temperature of the weldment is checked by using temperature-indicating crayons (commonly known as a ‘Tempilstik’). Temperature indicating crayons are designed to melt at pre-determined temperatures. A crayon for the appropriate temperature is used to mark the steel prior to heating and heating continued until the crayon mark is seen to melt. Alternatively, the appropriate crayon can be drawn along the heated steel.

**Steel Susceptibility**

The susceptibility of steels to hydrogen cracking is linked to the Carbon Equivalent (CE) of the parent metal. The CE is calculated from the percentages of various elements in the steel from the following formula:

\[
CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}
\]

where:

- \(C\) is the percentage by weight of Carbon in the steel
- \(Mn\) is the percentage by weight of Manganese in the steel
- \(Cr\) is the percentage by weight of Chromium in the steel
- \(Mo\) is the percentage by weight of Molybdenum in the steel
- \(V\) is the percentage by weight of Vanadium in the steel
- \(Ni\) is the percentage by weight of Nickel in the steel
- \(Cu\) is the percentage by weight of Copper in the steel.

Carbon Equivalent (CE) values may be determined from a chemical analysis, or requested from the steel supplier at time of order, by invoking an option in the specification of delivery conditions\(^3\). Maximum CE values are specified in the product Standards. Steel with higher CE values are more susceptible to hydrogen cracking.
3.4.2 Welding procedure specifications to BS EN 1011-2

BS EN 1011-2 (Annex C) demonstrates how appropriate welding procedure specifications may be developed which reduce the risk of hydrogen cracking. The factors taken into account are the CE value, the heat input, the hydrogen scale and the combined thickness, and determines what pre-heat (if any) is necessary. It is extremely unlikely that structural designers will be called on to prepare a welding procedure specification, which will invariably be prepared by welding engineers or similarly experienced personnel. The following example is included to give an insight into the process, and to demonstrate that a welding procedure specification is a balance of several different features.

To illustrate the use of Annex C, consider the development of a welding procedure specification for the T-joint shown in Figure 3.4.

**Step 1 - Carbon Equivalent**
If the steel has already been supplied and its certificate is available, the CE value can be determined by reference to the manufacturer’s certificate. If the actual CE is not available, then conservatively, the maximum value in the product standard may be assumed. In this example, the maximum value from Table 4 of BS EN 10025 will be used, which has been taken as the maximum CE for S355 steel for thicknesses up to and including 40 mm.

In this example, a CE of 0.45 will be assumed.

**Step 2 - Hydrogen Scale**
Hydrogen Scales are quoted by the consumable manufacturer, but to assume a mid-range (Scale C) for welding in a fabrication workshop is generally satisfactory. On site however, atmospheric moisture levels are likely to be higher than in a workshop environment, and for the purposes of this example, Scale B will be assumed.

**Step 3 - Heat input**
Heat input can be determined by trials, or estimated from previous experience. Typically, a heat input of between 1.6 kJ/mm and 2.7 kJ/mm would be a reasonable range for most joints. A lower heat input is the more conservative value. A heat input of 1.75 kJ/mm will be assumed in this example.

**Step 4 - Combined thickness**
As shown in Figure 3.4, the combined thickness is $40 + 40 + 40 = 120$ mm.
Step 5 - Pre-heat requirement

BS EN 1011-2 contains a number of figures for different hydrogen scales and CE values. In this example, for a CE of 0.45 and hydrogen Scale B, the required minimum pre-heat is determined from figure (2e), reproduced below (Figure 3.5). The intersection of the heat input of 1.75 kJ/mm and the combined thickness of 120 mm falls between the 100°C and 125°C lines, indicating that a minimum pre-heat of 125°C would be required in this example.

![Figure 3.5 Minimum pre-heat temperature for Hydrogen scale B and a maximum CE of 0.45 (Figure C.2e from BS EN 1011-2)](image)

Note that the requirement for pre-heat (which is generally expensive and inconvenient) may be reduced or avoided altogether by using steel with a lower CE value, or by increasing the heat input. Also, the actual CE may be significantly lower than the maximum stated in the Standard. The advice of a welding engineer may prove invaluable at this stage to suggest the most appropriate balance of variables. From the example, it will be noted that pre-heat is more likely to be required as the CE value increases and the combined thickness increases.

3.4.3 Other issues

In addition to the guidance on the avoidance of hydrogen cracking, BS EN 1011 also covers lamellar tearing, solidification cracking and material hardness in the heat affected zone. These aspects of welding are common to both shop and site welding, and not exacerbated by site conditions. If advice on these topics is required, the reader is referred to BS EN 1011 and the Bibliography (Appendix B), and advised to obtain advice from expert sources.

Lamellar tearing

In joints where welding contraction strains act in the through-thickness direction of a plate, lamellar tearing may occur. Such tearing is a concern mainly in plate, and mainly occurs during production, not during service. The risk of lamellar tearing may be reduced by:

- Using plate which is resistant to lamellar tearing, specified to BS EN 10164[^13].
- Reducing weld shrinkage (reduced volume of weld, fewer weld runs).
- Modifying the detail to avoid through-thickness strains.
Solidification Cracking

Solidification cracking usually affects the weld metal, typically along the longitudinal centreline of the weld. Such cracking is most commonly found in sub-arc welding, less frequently with MIG, MAG and FCAW, and rarely in MMA welding. The risk of solidification cracking is reduced by:

- Use of low carbon, low impurity consumables.
- Slower welding speeds, especially on the more susceptible root runs of butt welds.

Material hardness

In the heat-affected zone of the parent metal, both toughness and material hardness will be changed. The changes in both these mechanical properties are managed by controlling the cooling time, itself influenced by the heat sink, the heat input and any pre-heat.

Note that the use of approved welding procedure specifications should ensure that satisfactory production welds are completed without cracking, and without unacceptable changes to the mechanical properties. The welding tests described in Section 3.3 are designed to mirror the production welds in every respect, and involve comprehensive tests of the weld and the heat-affected parent material to ensure that the production welds may be completed satisfactorily.

3.5 Approval of welders

Welder qualifications to BS EN 287 describe the competence of a welding operative, which has been examined by the completion of appropriate test pieces. A welder approved to BS EN 287 is approved to weld a range of joints depending on the original examination undertaken, covering for example, material thickness, joint type and welding position. It is important that the welder is qualified for the specific circumstances of the joint being welded, and this is discussed below.

Welding operatives must demonstrate competence by successfully completing a test joint (which may be the same joint used to demonstrate the adequacy of the welding procedure). The welder approval test certificate contains details of the test, and also the range of approval for which the welder is qualified. The range of approval covers welding process, joint type, material thickness and welding position. Welder approval test certificates remain valid for two years, provided the certificate is signed at six month intervals by the employer, and the welder is engaged with reasonable continuity in the type of work covered by the certificate. Engineers invited to review a welder approval test certificate may find the following basic checklist helpful:

1. Is the certificate up to date, and not more than two years old?
2. Is the process to be used covered by the certificate?
3. Is the thickness of the joint within the approved range?
4. Will all welding be carried out in positions covered by the certificate?

Comprehensive guidance on the range of welder approval following the satisfactory completion of a weld test piece may be found in BS EN 287-1.
4  WELDING OTHER MATERIALS

4.1  Galvanised steel

Galvanised steel is an otherwise conventional structural steel with a hot dip zinc coating. If the zinc coating is locally removed then this material can be welded by the same methods as uncoated steels. It is recommended that the zinc coating be removed to at least 25 mm on each side of the joint. If there is any zinc remaining in the weld area, contamination of the weld pool will lead to a defective weld.

The problems that can result from zinc contamination of the weld are:

**Weld embrittlement**
The weld metal is more brittle, and more susceptible to cracking.

**Porous welds**
Porosity is likely to occur because of the gaseous fumes made by the volatilisation of the zinc.

**Welding difficulty**
The energy balance of the arc is disturbed by the zinc vapour in such a way that the current drops, so giving reduced penetration.

**Spatter**
Spatter (solidified molten spray) can lead to damage to the remaining galvanizing. Spatter generally increases if zinc vapour is present in the welding arc.

In addition to the problems with weld quality, there is a serious health and safety hazard which arises when welding galvanised steel. The volatilising zinc produces a fume which if inhaled can cause ‘zinc fever’. The symptoms are similar to those of influenza i.e. aching limbs, indisposition, increased salivation, shivering fits and possible vomiting. There is no apparent permanent damage is caused, and recovery normally occurs within 24 hours. Adequate ventilation is essential so as to avoid inhalation of welding fumes or, alternatively, breathing apparatus may be provided.

4.2  Painted steel

Painted steel, or any contamination of the steel surface, including rust, can lead to deficient welds as a result of solid inclusions, lack of fusion, cracks or porosity. The mechanisms and results are similar to those described for galvanised steel and the same precautions should be adopted.

All surfaces to be incorporated into the weld itself should be thoroughly cleaned of all coatings or contaminations, and dry, immediately prior to welding. Steel may be cleaned by chemical means, or more commonly by mechanical means; typically grinding.

Occasionally, steel may be coated with special ‘weld-through’ primers, which have been formulated and demonstrated to make only a marginal difference to the hydrogen levels. Welding without removing this primer is acceptable. Note that the approved WPS for such situations (see Section 3.3) should include the primer, if this is to be present in the production welds.
4.3 Cast iron

Welding of cast iron under any conditions, especially those that may be met on site, is not advisable.

Cast iron is probably more diverse than steel in the number of types and range of mechanical properties. Some of these types are (just) ‘weldable’ but they require very special welding procedures that are outside the scope of this document: most types of cast iron are completely unweldable.

Once the material identity is established as cast iron, the services of a welding engineer will be essential. The techniques and welding consumables for these operations are very specialised so it is essential that expert assistance is sought.

4.4 Wrought iron

Although wrought iron is not commonly specified in new construction, wrought iron is frequently encountered on refurbishment projects; site welding may be proposed as part of the refurbishment work. In such cases the first challenge to be met is correct identification. A metallurgical analysis of the iron is necessary to confirm that it is a wrought iron, and not steel or cast iron. The uncertainty is common, as both wrought iron and steel can be similar in appearance (riveted/painted/rusty) and both were used in construction during the period 1860-1900.

The metallurgical analysis can also give information on strength and chemical composition, while metallography will establish the density of slag fibres. The slag fibres are lines of inherent weakness in the iron and are formed during its production. The fibres are randomly spaced in the piece of iron but are aligned along its axial direction.

The weldability of the wrought iron is affected greatly by the density and orientation of the slag fibres. The presence of these fibres can lead to low through-thickness strength in the parent material, resulting in some ‘good’ welds which tear the wrought iron apart by stressing internal defects in the wrought iron.

Wrought iron is far more tolerant of strains acting along the axis of the slag fibres, so where a fillet weld would fail (Figure 4.1), a butt weld may provide a serviceable connection (Figure 4.2). However, in no situation should a wrought iron welded connection be used where fatigue conditions are likely or where it is to be a critical element of the structure.

![Figure 4.1](image.png)  
*Figure 4.1  Detail susceptible to failure in wrought iron*
Before the choice is made to weld wrought iron, it would be wise to consider mechanical connection systems, such as bolting or rivetting. Should welding be the only viable option the following steps should be taken.

1. Metallurgical Analysis to determine the following:
   (a) Chemical analysis.
   (b) Mechanical properties.
   (c) Metallography.

2. Consult a Welding Engineer:
   (a) To determine the viability of welding
   (b) To assess how the weld configuration can be arranged to provide best chance of success
   (c) To evaluate the types and magnitudes of forces that can be carried by the proposed joint, noting that the parent material may be the critical link.

3. Conduct welding trials, with associated testing.

**4.5 Welding reinforcing steel**

Since the introduction of BS 7123\(^{(14)}\), there has been greater confidence in the success of welding steel reinforcement for concrete on site, although there have been difficulties in making sure the welding procedures were properly developed and followed. Using BS 7123, it is possible to prepare appropriate welding procedures for welding reinforcing bars at intersections, laps and cruciform joints, for all types of reinforcement complying with BS 4449\(^{(15)}\) and BS 4482\(^{(16)}\). Reinforcing steels to these Standards must be weldable. This weldability is achieved by controlling the chemical composition and hence carbon equivalent (CE) values. Reinforcing steels having a CE less than 0.51 are classified by BS 7123 as ‘more readily weldable’. Reinforcing steels having a CE more than 0.51 will require more onerous welding procedures to avoid defects.

Satisfactory strength levels are maintained in the welded bar through a combination of good weld design and by good welding practice, both of which are covered within BS 7123.
However, tack welding of reinforcement continues to cause great concern. Contrary to popular belief, small tack welds create more metallurgical problems than large full strength welds. For this reason, tack welds must have a minimum specified size and length in accordance with Clause 11.6 of BS 7123.

4.6 Welding stainless steel to structural steels

In the search for more efficient and durable buildings, engineers often select different metals for different applications within the same structure. Quite frequently, this may result in the use of a stainless steel (specified in an area of high corrosivity, or for a special architectural feature) which needs to be joined by welding to a carbon-manganese structural steel frame.

One of the first things that will be selected by the engineer is the type of stainless steel. There are basically three types of stainless steel:

1. Austenitic
2. Ferritic
3. Martensitic

The structural engineer would normally only be choosing between either austenitic or ferritic stainless steels; the martensitic steels will probably be too hard and brittle to use and are traditionally associated with applications such as surgical scalpel blades.

The choice between ferritic or austenitic stainless steel will probably be guided by the degree of stain resistance being sought, which in turn is a function of the environment in which the material will operate. For the types of applications usually encountered by structural engineers, it is most probable that austenitic stainless steel will be chosen.

Austenitic stainless steel contains a high degree of alloying involving chromium, nickel, molybdenum, etc. as well as carbon. Welding one of these steels to a carbon-manganese steel obviously leads to a mixture of the two in the weld pool. Since the resulting welds are metallurgically quite complex, it would be normal practice to take advice from a qualified welding engineer. The person responsible for devising the weld procedure would generally, first consult the welding consumable manufacturer for his recommendations as to consumable and weld procedure, and then have that procedure proven by the fabricator according to the requirements of BS EN 288.

Most of the larger steelwork contractors have some experience in the welding of stainless steel to structural steels, and already have appropriate welding procedure specifications. In all circumstances, welding should be carried out to a proven welding procedure specification.
5 SITE PRACTICES AND PROCEDURES

5.1 Location of the work

The principal difference between shop and site work is that on site, there are few fixed facilities or permanent shelter available. Site practices are therefore largely concerned with providing access, supplies, and if necessary, shelter at the workplace. The second major difference is that site welding involves holding the parts to be welded in their correct positions (which itself may be no small task), and then welding the “as erected” joint, in whatever location, orientation or elevation the joint is planned. The convenience of assembling parts in the workshop, usually without restraint, and the opportunity to turn items for easier assembly or access to weld, is generally not possible on site.

The actual processes of welding and cutting differ very little from the equivalent process in the workshop.

5.2 Equipment for welding and cutting

The overriding criteria for selecting equipment for site welding or cutting are that the plant should be suited to the site environment and should not be sensitive to being moved or set up in temporary conditions. The equipment must also be able to tolerate the sorts of environment and level of use found on site. Suitability for site might include a resistance to interference from dirt, dust or other debris. For example, the wire feed system on a FCAW machine must be able to tolerate the bits of grit which will inevitably form a part of a building site environment without jamming or affecting the wire feed speed. It is also important for the plant to tolerate being wet and, if drenched, then it should be easy to disassemble and dry out.

The principal item of equipment for welding is the power source. A wide range of generators is available for site use, from small units that can be carried in a van to large units that can supply several welders simultaneously. Generators usually need to be located close to the workplace.

Flame cutting equipment requires bottled gas consumables, which though large, are transportable around site.

Equipment selection will be the responsibility of the contractor. For the structural designer, the consideration of the hazards associated with site welding, the need to provide access and protection, and the impact of site welding on other trades are of more concern.

5.3 Health and safety issues

The health and safety of personnel engaged in construction activities (and those affected by construction) is a key concern, particularly during the site construction phase. The Construction (Design and Management) Regulations 1994 (commonly known as the CDM Regulations) were introduced in the UK to address the poor record that the construction industry has for the health and safety of its employees, particularly on construction sites. Everybody involved in the design, planning or execution of construction works now has a legal
responsibility to consider hazards to health and safety as a part of their duties and to minimise these risks wherever possible.

Best practice, as directed by the CDM Regulations is for all involved in construction work to consider where they might have an opportunity to reduce the hazards and risk associated with construction activities. For designers, this must involve a consideration of how a structure will be built, assessing the risks involved, and assessing safer ways of working. The CDM Regulations do not demand that health and safety issues dominate the design process, but that health and safety must be considered at the same time as aesthetics, cost, programme etc.

Site welding and cutting clearly involve a number of potential hazards, which include:

- High current electricity
- Eye hazards from the very bright arc, and UV radiation
- Eye hazards from weld spatter
- Particles during grinding
- Noxious and possibly inflammable fumes
- Hot and sharp metal
- Compressed (and sometimes explosive) gases
- Noise, dust and vibration
- Workplaces which may be at height, and operations which necessitate the use of equipment for considerable periods.

Exposure to these hazards is not limited to the welder alone. Adjacent trades, other construction workers and possibly the general public may also be exposed. All must be considered when carrying out risk assessments.

Site welding can be carried out safely with appropriate measures to protect the welder and others who may be affected. Basic measures of providing appropriate safe access to all worksites, working platforms if necessary, excluding others from the worksite during the welding operations and wearing the appropriate personal protective equipment should ensure site welding is no more hazardous than welding in the workshop. Welding is an established practice, carried out by experienced personnel (see Section 3.5) and can be conducted safely.

### 5.4 Weather protection, dampness and contamination

The most obvious and most significant difference between shop and site welding is the weather protection afforded in a fabrication shop compared to the exposure to the elements that may be experienced on site. Rain, wind and low temperatures can all have a substantial adverse effect on the quality of welds produced, as well as affecting the rate at which the welding can be carried out.

Rain, or surface moisture on the steel (from condensation or dew), can affect the quality of the weld itself, as it will increase the amount of hydrogen in the weld pool, and the quenching effect will increase the cooling rate. Both of
these effects increase the risk of hydrogen cracking, as discussed in Section 3.4.1. In addition, rain or snow obviously makes any activity involving electricity more hazardous.

Whether raining or not, conditions of high humidity in the atmosphere may also mean that moisture is absorbed into the flux of MMA electrodes, again increasing the hydrogen content in the weld metal. Electrodes should be stored in dry conditions, and should not be taken from their sealed packets before they are to be used. Some electrodes will require baking, and then storage in heated quivers to reduce the hydrogen content in the weld – the manufacturer’s instructions should be followed.

The effect of wind on the welding process is that it can disturb or even destroy the gas shielding around the arc. This will have a direct effect on the visual appearance of the weld and, more importantly, on the mechanical properties of the weld.

The symptoms of a disturbed gas shield include:

• a difficulty experienced by the welder in maintaining a stable arc during welding
• higher than normal levels of spatter and porosity in the weld metal after welding
• a lumpy or irregular weld bead.

These symptoms indicate that the mechanical properties of the weld are likely to have been compromised. Welding operations should be stopped and any suspect welds removed.

The effect of low temperatures is to increase the risk of hydrogen cracking. The low ambient temperatures on site must be taken into account when the need for pre-heating is established during the determination of an appropriate weld procedure specification (see Section 2). A calculation which demonstrates that a zero pre-heat is required is based on the assumption that the ambient temperature is about +10°C, whereas steel on site may be as low as −15°C.

It is common to provide some form of protective shelter to protect the welding from wind and rain. Figure 5.1 shows a typical lightweight shelter that can be completely closed to provide a warm, dry, protected environment.

![Protective shelter for welding operations](image-url)
5.5 Effects of other trades

Construction sites are busy areas especially when programme pressures dictate that many varied activities must take place simultaneously. Under these circumstances, construction planners must consider how adjacent activities will affect the site welding operations and what effect the welding activities will have on others.

Within the scope of this consideration will be:

- **Feasibility** - which operations can and which cannot physically take place at the same time as welding?
- **Sequence** - which operations must take place before the welding, and which must follow the welding?
- **Logistics** - are the raw materials, plant and equipment in place on site when it is planned for the welding to take place?
- **Resources** - will the mains electricity or generating capacity be in place when welding is planned to take place?
- **Manpower** - does the welding operation depend upon existing unskilled or semi-skilled labour to assist in any part of the work?
- **Health and Safety** - will the measures taken to manage the hazards associated with welding or cutting operations mean that other trades cannot progress their own operations until the welding is complete?

For all of these activities, it is necessary to determine just how close in time and space they can afford to be to one another and then create safety zones around them. Programme contingencies should be made to ensure that any slippage does not prejudice the success or safety of the project.
6 DESIGNING FOR SITE WELDING

This Section offers advice on the practical issues that should be considered when proposing site welding. The advice is offered assuming that most of the fabrication operations have been completed off site, and the site work is required to complete or modify components brought to site. The following Sections are not intended to apply to dedicated on-site fabrication units, when the controlled environment of a workshop is established on site.

6.1 The need for site welding

Site welding is commonly thought of as necessary in remedial works, and less frequently considered as an appropriate process at the design stage. Site welding is however, an appropriate technique for the designer to consider at an early stage, even for new works.

Site welding may be proposed at the design stage in the following circumstances. The list is typical, but not necessarily exhaustive:

- Welding may be the only feasible way to complete a heavily loaded site connection. A lack of space, aesthetic considerations or simply the magnitude of the applied forces may make a connection formed of bolts and other components an unacceptable solution.
- Welding may form a convenient connection to existing steelwork, particularly in refurbishment projects. A lack of access to the back of partially exposed existing steelwork may preclude a bolted connection.
- Welded connections are generally considered to be more aesthetically attractive, compared to bolted connections, and may be specified for highly visible connections.
- Bolted connections may be very difficult to achieve without substantial alteration to the members. Connections between circular hollow sections are not suitable for bolted details without substantial modification to the ends of the members. A welded connection between such members may be preferred for both structural and aesthetic reasons.
- Welded connections are generally stiffer than bolted details. This may be particularly important where connections carry moment, and the analysis has assumed rigid connections. Connections detailed with ordinary bolts in clearance holes allow significant slip, which may be very detrimental to both ultimate and serviceability performance. Vierendeel girders and splices carrying bending moments are two examples of where rigidity is important and where welding may be an attractive solution.
- On some projects, notably refurbishment, site welding may be deemed to be more economic overall. Access requirements to drill existing steel are the same as required for welding, which may mean that welding is an equally attractive, or more attractive proposition. The costs of setting up for site welding and then moving to different locations can be relatively very significant if only a small number of site welds are required. If equipment and operations are established for a significant site welding programme, the proposal can be more economically attractive.
6.2 Construction issues

When comparing site welding to conventional bolted construction, the major considerations are health and safety, and the effect that the welding operations may have on the construction programme.

Health and safety considerations were covered Section 5.3. The hazards associated with site welding can be properly managed, but the effect of, for example, exclusion of following trades from the area around the welding, should be considered in the construction programme.

The following construction issues should be considered.

Temporary support

In general, the connections to be welded on site will contribute to the load carrying capacity and the overall stability of the structure. Temporary works may therefore be required, performing three quite different functions:

- to provide local support at the joint, so that the members may be aligned prior to welding
- to support applied loads until the structure is completed by the welding operations
- to maintain overall frame stability (if stability in the final state is provided by the welded connections).

The provision of such support may be a significant operation both in design (the temporary case will be an important design case) and in the construction sequence.

Access

Conventional bolted construction is commonly completed by operatives in mobile elevating work platforms (MEWPs) (commonly known as ‘cherry pickers’ and ‘scissor lifts’) generally used from within the footprint of the structure. This type of working platform may be equally appropriate for site welding, if the joints to be welded are relatively straightforward. Depending on the joint type and location, rather more fixed temporary access may be required for complex welds or where access from a MEWP is not possible. Welding operatives are likely to need clear access to both sides of a particular connection, and will need cabling between the power source and workplace. Temporary decking, edge protection and weather protection may be necessary, which may all have implications on the construction programme.

Plumbing, levelling and lining

Bolted structures are usually plumbed, levelled and lined in a two stage operation – rather coarsely as the structure is erected, and subsequently to the specified tolerances as the connections are completed (fewer bolts may be installed initially) and bolts tightened. In site welded structures, the plumbing, levelling and lining operation must be carried out prior to the welds being completed, as the welding will ‘fix’ the structure with only a small degree of subsequent adjustment possible.

The structure does not have to be entirely complete before the plumbing, levelling and lining operations, and welding, can continue. Frequently, the alignment and welding is completed in zones, allowing subsequent construction activities to continue.
**Inspection and corrosion protection**

Both the inspection of the finished welding and, assuming the welds are satisfactory, the application of the corrosion protection system (and/or fire protection system) necessitate appropriate access, and need to be recognised as important operations on the programme. Whilst application of the corrosion protection system may not be on the critical path, timely inspection of finished welds is important if subsequent construction activities would make remedial work inconvenient or difficult.

**Provision of information**

To adequately price welding operations and the related provisions for health and safety, and to allow appropriate time in the programme, designers should highlight where site welding is envisaged. The need for site welding should appear in the designer’s declaration of the assumed construction process, but additionally, site welding should also be indicated on the contract drawings. The standard identification for a site weld is shown in Figure 6.1, in accord with BS EN 22553[^17]

![Figure 6.1 Symbolic indication of site weld (BS EN 22553)](image)

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**6.3 Practical considerations for site welding**

This Section describes the practical issues to be considered by the designer when proposing site welding, illustrating a number of common solutions used in practice.

**6.3.1 Assembly aids**

Even simple joints will need to be properly aligned and located with respect to each other, to relatively tight tolerances (less than 5 mm). This will always necessitate the use of some device both to hold and to adjust relative positions. At the simplest levels, packs and wedges may suffice. More commonly, restraint and adjustment will be provided by some form of threaded bar and cleat arrangement.

Before proceeding with the design of such arrangements, it is important to decide whether they are to be used simply to align and restrain the items to be joined, or whether they are also to carry the temporary (but possibly very substantial) member forces. Any alignment system usually induces significant eccentricity to the line of any member force, as any secondary components used...
to restrain and align the joint must be sufficiently distant to allow clear access to the weld.

Figure 6.2 shows a simple landing cleat and draw bar to provide vertical and longitudinal positioning. Vertical adjustment is by means of packs between the cleat and the beam. Note that this simple arrangement could not be relied upon to make any contribution to frame stability, which would have to be provided by other means.

Figure 6.2  *Landing seat and draw bar in beam/column connections*

Figure 6.3 shows a more elaborate arrangement of specially fabricated cleats and draw bars to hold two ends of a circular hollow section in correct alignment. In the actual project, the hollow sections formed the main chords of substantial pre-fabricated truss arrangements. It was (correctly) anticipated that significant force would be needed to align the joints prior to welding. Note also the joint preparation and backing strip, which were fabricated off-site. These types of detail are discussed in Section 6.3.3.

Figure 6.3  *Temporary support to CHS joint*
Figure 6.4 shows a rigid secondary member (known as a ‘strong back’) to align two plates to be joined without a change of direction at the weld.

In the examples of Figure 6.3 and Figure 6.4, considerable effort has been expended in providing the temporary works arrangements, which have themselves involved welding secondary components to the primary members. In both cases, after the welding is complete, the temporary works must be removed, which may itself be a significant operation involving cutting, grinding and replacement of the corrosion protection system. Aesthetic considerations or sensitivity to fatigue may limit where such secondary components may be located.

Refurbishment work will almost certainly involve site surveys to determine the details of any new steelwork required to fit into the existing structure, but despite the surveying effort, good practice is to make provision to accommodate any lack of fit.

Typical solutions would include support cleats, fin plates and similar fittings of generous proportions, so that a range of dimensions can be accommodated. The new member, the existing works and the connection components, including the weld, need to be designed for the most onerous loadcase.

### 6.3.2 Access to weld

In addition to the need to provide access for the welder (and inspector) to reach the joint location, the fabrication details themselves must allow the welder to complete the weld. The welder will no doubt be wearing gloves, may have an electrode that protrudes some 300 mm from the welding gun, and obviously needs to be able to see the joint itself. Some appreciation of the physical size and relationship of the components is necessary for the designer to appreciate whether welding is possible. A revised assembly order, or a different arrangement of the pre-fabricated components, may be possible if access to weld is difficult. Difficult access situations should be avoided, as the difficulty in providing a high quality weld will increase. Inspection may also be difficult or impossible, conspiring to make the most difficult welds the ones that receive least quality control; this should be avoided by revising the detail.

### 6.3.3 Weld procedures

On site, the emphasis should be on making the welding as straightforward as possible to reduce the risk of defects in the welds. This involves the use of backing plates and dowhand welding wherever possible.

Downhand welding simply means that the molten weld pool is lower than the electrode – the ‘easiest’ position to weld. At the other extreme, overhead welding, involving welding with the molten weld pool above the electrode, requires considerably more skill on the part of the welder. Defects are more likely in the overhead position. Unlike the workshop where elements can be rotated, site welding may well involve welding in all positions, and the reader is
reminded of the requirement of all welders to be certified as competent for the welding to be undertaken, as described in Section 3.5.

Backing strips form an external overlap to an open weld, which much improves the ease of welding and leads to a reduced risk of defects. A backing strip is shown in Figure 6.5 at a butt joint in a plate.

**Figure 6.5  Backing strip to butt joint**

Backing strips may be ceramic, or made of steel strip. Ceramic backing strips are commonly supplied with a self-adhesive strip, and simply stuck to the parts to be joined. Ceramic backing strips may be removed after completing the weld. Steel backing strips are fused into the weld, and not removed unless there are special reasons to do so. Steel backing strips should be of similar grade and properties to the parent metal, since the steel from the backing strip forms part of the molten weld. Whenever backing strips are used, the welding procedure specification (described in Section 3.3) should include the use of a backing strip.

Figure 6.6 shows a beam to column connection with the flange joints both prepared as downhand welds, and backing strips under each joint. The backing strips are tack welded into position after the beam has been located and aligned correctly. The fin plate and bolts to the web are only used to locate and hold the beam until welding is complete, after which the bolts are removed. The fin plate also acts as a backing plate for the web weld.

**Figure 6.6  Beam to column connections prepared for site welding**

The use of backing strips does not mean that alignment of parts can be neglected. Gaps between the backing strip and the element, as shown in Figure 6.7, could lead to contamination at the root of the weld, and should be avoided by provision of secondary systems to align the members.
As far as possible, preparatory work to facilitate site welding should be completed in the fabrication workshop, prior to shipping. This includes the additions such as the alignment and restraint system, joint preparation and backing strips. With the exception of the weld itself and the draw bars, all the details shown in Figure 6.3, including the backing strip, were assembled and fabricated in the workshop.

Figure 6.8 shows a joint detail where off-site preparation has minimised the amount of site work. It shows a splice in a thick-flanged column that is to be site welded. In addition to the plates used to locate and support the connection, the joint preparation (for a partial penetration weld) can be seen. A length of sealing plate has been omitted so that the weld can be properly completed at the inside corner of the flanges. Once the weld is complete and tested, the missing plate will be welded in position.

6.3.4 Local welding effects
The designer should be aware of the local effects caused by welding, which include:

- expansion due to any pre-heat applied
- expansion due to the heat input during welding
- contraction during cooling
- temporary reduction in material yield strength.

None of these effects are unique to site welding; all occur in the fabrication workshop. The circumstances on site may mean that the effects are more important. Expansion is not likely to be a problem, unless other brittle
components are connected to the steel, perhaps in refurbishment work, or if existing steelwork is built in very rigidly. Contraction may be an increasing problem as welding proceeds, due to the increasing rigidity of a fabrication. The later welds around a heavily stiffened fabrication may experience considerable tensile stress due to their own contraction on cooling, if the fabrication itself does not strain. Stress due to cooling (contraction) is more of an issue in smaller, heavily stiffened fabrications, when advice should be sought on appropriate techniques and welding programmes to minimise the risk.

Very high temperatures cause a temporary reduction in yield strength. Figure 6.9 shows the variation of material strength with temperature for carbon-manganese steel.

![Figure 6.9 Variation of steel strength with temperature](image)

Local to the weld, temperatures momentarily reach the melting temperature – about 1500°C. The temperature in the parent metal falls with distance from the weld, but the temporary loss of strength may be important if welding to already highly stressed existing steelwork. During welding, the penetration depth will be molten, equivalent to a loss of section. In addition, the adjacent steel will have reduced design strength, resulting in a further reduction of local resistance. In most cases, the lower levels of load during construction, and the very limited zone of strength reduction will mean the temporary reduction in strength may be ignored. In extreme cases of welding to highly stressed members, the effect should be considered.
6.4 Strength design of site welds

The quality of site welds should be no less than welds in the fabrication workshop; no different rules or any other factors are applied to the structural design of site welds. Some prudence may be advised in the assumptions regarding depth of penetration in partial penetration butt welds. BS 5400-3[10] states that if the preparation is the V type (Figure 6.10) or the bevel type (Figure 6.11), the throat thickness of a partial penetration butt weld should be taken as the depth of the weld preparation, less 3 mm. This provision is not in BS 5950-1:2000 (it was in the 1990 version) but would appear a prudent measure for site welding, anticipating that in the more difficult site conditions, penetration may not extend to the full extent of the preparation. No such reduction is required if procedure trials (which should reflect the site conditions) demonstrate that reduction is not necessary.

![Figure 6.10 V butt weld](image1)

**Figure 6.10 V butt weld**

![Figure 6.11 Bevel butt weld](image2)

**Figure 6.11 Bevel butt weld**

Designers should note the attractions of partial penetration welds with superimposed fillets (or reinforcing fillets) shown in Figure 6.12, which are straightforward, minimise joint preparation and weld volume, and are therefore economically attractive.

![Figure 6.12 Partial penetration butt weld with superimposed fillets](image3)

**Figure 6.12 Partial penetration butt weld with superimposed fillets**

For parts of connections which are subsequently overlapped by another member, as shown in Figure 6.13, it should be clearly specified by the designer whether the overlapped part is to be welded, or not.
6.5 Relative welding costs

Table 6.1 shows indicative relative welding costs for different weld sizes, weld types and welding positions, all related to a 6 mm fillet weld formed in the downhand position. More weld, but of a smaller leg length, is generally preferable, and fillet welds preferred over butt welds. Table 6.1 does not account for the additional costs of joint preparation for the butt welds, or the costs of inspection.

Table 6.1 Relative welding costs related to a 6mm downhand fillet weld

<table>
<thead>
<tr>
<th>Weld</th>
<th>Downhand</th>
<th>Vertical</th>
<th>Overhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 fillet</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>10 fillet</td>
<td>3</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>10 butt</td>
<td>4</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>20 butt</td>
<td>12</td>
<td>18</td>
<td>24</td>
</tr>
</tbody>
</table>

Figure 6.13 Overlapping members to be welded
7 ASSURING THE QUALITY OF SITE WELDING

The quality of site welds – their strength, integrity and fitness for purpose – is assured primarily by proper control of the whole process leading up to the completion of welding. Inspection and non-destructive testing after the welds have been made are a necessary part of the quality assurance process, but they should be seen as an opportunity to show how good the welds are, not how bad they are – it is better to find that there are no defects that need repair.

To assure weld quality, the materials used (parent material and consumables) must be known and appropriate, the work must be carried out to procedures that have been shown to be appropriate to the materials and working conditions, and the operatives must be suitably experienced for the particular type of welding. To control all these factors, records must be kept of tests carried out, procedures that have been devised and decisions that have been taken (for example judgements made where records, such as material certificates for existing structures, do not exist).

When carrying out inspection and testing, it must be remembered that nothing is perfect. Imperfections will always exist. It is therefore essential that acceptance criteria are established at the outset in the contract specification: imperfections within the specified limits will be acceptable and will not compromise the quality; imperfections outside the limits are defects that do compromise the quality and are likely to be unacceptable.

The following comments address the principal aspects of the quality assurance process for site welding.

Material

It is essential for satisfactory welds that the nature of the parent material is known (or at least, on the basis of experience and investigation, judged to be known). For new material, certificates should exist that record the properties and composition of the material. Welding procedures are only valid for a particular range of material and it should be confirmed that the welding procedure is appropriate for the material to be welded. For existing structures, the requirement for a reliable understanding of the nature of the existing material cannot be over-emphasised, as different materials can easily be confused.

Welding procedure specifications

Any welding that is carried out on site should conform to an approved welding procedure specification (WPS), as described earlier in the guide. Such a procedure will be valid for a particular range of materials, joint configuration, welding parameters, welding position and environment. The choice of procedure will be made on the basis of versatility and economic advantage. To achieve the required quality, the actual procedure that is followed must conform to the specification in all its aspects and to do this, full details of the WPS must be made available to the welder.
**Qualified personnel**

Application Standards require that the welder is properly qualified, in accordance with BS EN 287\[12\], for the process, material, joint type and welding position of the work. Site quality control should be such as to ensure that only properly qualified personnel are used; it is good practice to record who performs the welds, to ensure traceability in case of any systematic problems that arise.

**Working conditions**

As mentioned above, quality is only assured if the actual welding conditions are within the range for which the WPS is valid. This will mean that there must be proper access for the welder and that the joint is protected from the weather during welding (except, possibly, when work in an exposed situation can be delayed until there is fair weather). If conditions such as high humidity cannot be avoided when the work needs to be carried out, the WPS that is to be followed (in particular the choice of consumable) should be one that is valid for such conditions.

**Inspection**

Non-destructive testing should be carried out after welding, to confirm that there are no defects. For this, there must be predefined acceptance criteria that set out the limits of imperfections. In most cases, the National Structural Steelwork Specification\[18\] (NSSS) will be used; it represents standards of workmanship in building construction that are both reasonable and achievable, enjoying favour with designers and contractors alike. Note that the requirements contained in the NSSS are generally equivalent to those in BS 5950-2:2001\[9\]. The same specification should be used for the site works as is used for the off-site fabrication. The criteria given in the NSSS cover dimensional accuracy and weld imperfections such as undercut, lack of fusion, etc. which are discussed in Section 8. The NSSS also covers the requirements of welder qualification and welding procedure specification. Note that final surface inspection should not take place until a certain period (usually 16 hours) after the weld has been completed, so that any hydrogen cracking can be detected.

**Programme**

A realistic allowance for the welding operations needs to be made, as rushed preparation or execution will increase the risk of defective welds. The programme must allow for the temporary works (if any), access provision, local alignment at the joint, the welding operation itself and the weld inspection. On major joints in thick material, the pre-heating operation may be longer than the welding operation. As both form one continuous operation, the pre-heating must be planned for, and the effects included in the programme.
8 TESTING OF WELDS

8.1 Introduction

The inspection and testing of welds is an essential part of any site welding operation, to demonstrate that the necessary quality has been achieved. Although a satisfactory outcome depends largely on managing issues prior to the actual welding operation, there is a need to have positive objective evidence to show that the final outcome has been satisfactory.

It is sensible therefore to approach the testing of welds with the philosophy that this is an opportunity to show how good the welds are, not how bad they are. The extent, frequency and type of inspection should be defined in the contract specification, together with acceptance criteria that define when imperfections become unacceptable. The NSSS\textsuperscript{[18]} is recommended as the default specification on such matters.

Section 8 describes the role of inspection personnel, and the various methods of looking for weld flaws and determining if they are sufficiently bad to constitute defects.

8.2 The role of a Welding Inspector

It should be noted that an experienced and conscientious welding inspector can play a major role in ensuring welds are satisfactorily completed. The need for a welding inspector should be considered when the engineer specifies site welding. In effect, a welding inspector is equivalent to a specialist clerk of works, with appropriate delegated authority under the contract, reporting to the authority responsible for construction. The role covers the essential checking of welder qualifications, weld procedures, equipment etc., and the visual inspection of the welding. The importance of visual inspection cannot be overstated as problems with process, consumable, equipment or technique invariably manifest themselves in the completed weld run. If properly used, a welding inspector can prevent serious problems arising, leading to a much reduced weld failure rate and subsequent repairs.

The Inspector’s responsibilities may be briefly defined as:

(a) To ensure that the approved welding procedure is followed so that there can be confidence in the finished weld in providing the mechanical properties that the procedure testing has shown to be possible.

(b) To check welds for visible defects (such as undercut or under-size) so that they can be dealt with before other more elaborate and expensive examinations take place.

These responsibilities take place in three stages: before, during and after welding.

**Before welding**

The Inspector should be conversant with the applicable Standard, the welding procedure, the qualifications and capabilities of the welder and have a relevant set of drawings.
The inspector should check that:

- The weld preparation (including root gap and alignment) is in accordance with the approved and qualified weld procedure.
- That the whole of the weld area is clean.
- The electrodes, filler wires, shielding gases, etc., comply with the procedure and Standard requirements.
- If pre-heat is needed, it is applied in accordance with the procedure and, by using temperature indicating crayons or pyrometers, that it is evenly distributed throughout the joint.

**During welding**

The inspector should:

- Monitor the arc voltage, current and welding speed to see that they comply with the welding procedure.
- Ensure that de-slagging and cleaning is done on each run prior to further runs being laid, with particular attention being paid to the weld toes. Defects found at this stage should be repaired before further welding takes place.
- Ensure that the interpass temperature in multi-run welds is as specified in the procedure.

**After welding**

The inspector should ensure that:

- All slag is removed so that surface defects can be revealed.
- The penetration achieved in butt welds is acceptable to the Standard.
- The contour of the weld and the amount of weld reinforcement are acceptable.
- The length and size of the weld is in accordance with the drawing.
- The depth and amount of undercut is acceptable.
- The weld is fused to the parent metal at the weld toes.
- The whole weld area is checked for flaws and their acceptability to the Standard is determined.
- The weld and adjacent parent metal are free of unacceptable arc strikes.

When welds fail to meet acceptable standards and have to be repaired (either as a whole or in part), the inspector should:

- Ensure that the technique/procedure is appropriate and that the equipment is being used correctly if weld metal is to be removed.
- Ensure that sufficient material is removed to eliminate the defect completely.
- For a wholly removed weld, ensure that preparation of the re-weld complies with the qualified procedure.
- Ensure all repairs are carried out to a prior agreed repair welding procedure.
The same inspections specified for the original weld must be carried out for remedial work.

The inspector should ensure that records are kept to show that every item of the visual checklist has been completed. Welds that have received the necessary approval should be marked or identified in some distinctive manner such as paint or, if permitted, hard stamping.

8.3 Surface inspection

Surface imperfections and surface-braking imperfections are the easiest to detect. Apart from simple visual inspection, there are two principal methods used to disclose imperfections that cannot be detected by simple visual inspection; magnetic particle inspection and dye penetrant flaw detection.

8.3.1 Visual inspection

The NSSS[18] specifies that all welds be visually inspected. Although visual inspection will not detect fine cracks that other inspection methods disclose, visual inspection will provide an early indication of the weld quality, and detect basic imperfections. Visual inspection should cover the shape and size of the weld – which should accord with the drawings and specification. The throat thickness, profile, length etc. should all be inspected, with the assistance of gauges specially made to measure weld geometry. Visual inspection will also detect undercut (where the thickness of the parent metal is reduced adjacent to the weld toe), and spatter. Whilst spatter (globules of molten metal on the surface of the parent material) may not be detrimental, an excess of spatter, an irregular profile and a generally poor looking weld are all indicators that the integrity of the weld may be compromised.

8.3.2 Magnetic particle flaw detection

Magnetic particle inspection (MPI) is a popular technique because it is a rapid, low-cost way of detecting surface or near-surface cracks, inclusions, and porosity. It does, however, only work on ferrous materials so is not suited to finding defects when welding austenitic stainless steels.

The detection of cracks by magnetic means depends on the fact that the magnetic susceptibility of the ‘defect’ is markedly inferior to that of the surrounding ferrous material, causing the magnetic flux to flow around the fault seeking an alternative path. It is this magnetic flux leakage that makes magnetic particle inspection possible, and there are several methods by which it can be utilised. The simplest method is to apply finely divided iron in suspension in paraffin to the magnetised specimen.

This magnetic ‘ink’ is usually sprayed over the weld. The magnetic particles are attracted by the surface field in the vicinity of the fault, adhere to the edges of the defect, and so reveal the defect by a clearly defined accumulation of particles. The magnetic field may be produced with either an electro or permanent magnet.

The method of carrying out magnetic particle inspection begins with a thorough cleaning of the area to be tested. Next a contrasting background paint is applied to the surface to aid defect detection. This paint is typically white when used with the normal black ink. The position and orientation of the magnet depends on the plane in which the flaw is expected - for optimum detection, defects must
break the magnetic field at 90°. The application of the ink should take place whilst the material is magnetised. The ink is supplied in aerosols, and the instructions on the container should be followed. To view, lighting aids should be used if the daylight is poor and the area should be inspected from both sides of the magnet. Viewing should take place whilst the material is magnetised. Root undercut, lack of fusion, incomplete penetration, cold lapping and cracks all create a leakage field and give magnetic indications. Indications are difficult to interpret, and only experienced personnel should be expected to provide definitive reports.

8.3.3 Dye penetrant

Dye penetrant examination is easier to carry out than magnetic particle testing. The equipment is cheap and easy to obtain, and even the untrained can complete the process and achieve some form of results. However, the simplicity of the technique is misleading because the processes involved in carrying out dye-penetrant examinations are very sensitive to incorrect application and, under these circumstances, often give spurious results. Dye penetrant tests should therefore only be carried out by a fully trained and qualified tester.

The basic principles of dye penetrant testing rely upon a highly visible ink penetrating into tiny cracks and crevices, and then being drawn out from a cleanly wiped surface by, say, chalk dust.

The concept is simplicity itself, and this together with its ability to work for even poorly trained personnel has lead to its widespread adoption in a host of metal industries, particularly for foundries.

Dye penetrant testing is much more sensitive to lack of cleanliness than magnetic particle inspection; to be thorough can lead to a need for wire brushing and finishing with a fine wet and dry emery. In extreme circumstances, it can even be recommended that an acid etch should precede the testing. It has been known that because the whole concept relies upon the ink penetrating crevices, an overly zealous cleaning process can actually hide the defects by smearing metal over a crack and therefore preventing detection. Dye penetrant is also unable to reveal the just-subsurface defects that magnetic methods can.

One area where dye penetrant examination is particularly valuable despite being less sensitive or probing than magnetic methods is where the material under consideration is non-magnetic. MPI will obviously not work on these materials and this can be quite a handicap because, apart from the obvious metals such as aluminium, copper, brasses and bronzes etc., most stainless steels will also not respond to an induced magnetism.

Dye penetrant examination methods can have a very important role in the testing of site welds, but it is as well to remember that it is a messy process, it requires a substantial amount of careful preparation, and is not as sensitive as other techniques. For austenitic stainless steels it may be the only surface defect detection process available.
8.4 Sub-surface inspection

There are two principal methods that can be used to detect sub-surface imperfections; ultrasonic testing and radiography.

8.4.1 Ultrasonic flaw detection

Ultrasonic methods of non-destructive testing use beams of high frequency/short wavelength mechanical waves (vibrations) transmitted from a small probe and detected by the same or other probes. Such mechanical waves can travel long distances in fine grained metals.

Usually, pulsed beams of ultrasound are used and, in the simplest instruments, a hand-held single transmitter/receiver probe is placed on the specimen surface. An oscilloscope display with a time-base shows the time it takes for an ultrasonic pulse to travel to a reflector (a flaw, the back surface or other free surfaces) in terms of distance across the oscilloscope screen - the so-called A-Scan. The height of the reflected pulse is related to the flaw size. The relationship of flaw size, flaw distance and flaw reflectivity are complex, and considerable skill is required to interpret the display.

There are two fundamental methods of ultrasonic examination: Transmission method and Reflection method.

Transmission method

In this method, two probes are used, one to inject the signal into the specimen and another probe directly opposite to receive the signal. Any flaw will reduce the signal reaching the receiver probe and thus the existence of a flaw can be inferred from the loss or degree of loss of the original signal. There are, however, some disadvantages in using this method:

- The specimen must have parallel sides.
- It must be possible to reach both sides.
- Two coupling points are required.
- No indication is given of the position of the defect.

Reflection method

In this method, only one probe is used which transmits and receives any reflected ultrasound. The advantages of this technique over the transmission method are:

- Access is only required from one side.
- Only one coupling point is necessary.
- Irregular shapes can be examined.
- The position of defect can be determined.

For most ultrasonic flaw detection and inspection, the reflection method is preferred.

With both the transmission and the reflection method, it is essential that a couplant be used (grease, oil, water, etc.), to eliminate any air gap between the probe and the metal so as to allow the ultrasonic vibrations to penetrate the metal.
The application and interpretation of ultrasonic flaw detection is a highly skilled operation; only approved operators should be used. An operator must have undergone an intensive technical and practical training scheme, with a rigorous examination to establish competence. Most such approval schemes are also subject to renewal every few years, with the option of a re-test if there has been a lapse in continuous working at the most demanding level.

8.4.2 Radiography

The use of radiographic examination of welds on site is very rare because of the health issues associated with the ionising radiation used to penetrate through the metal to leave an image on a photographic film on the far side of the joint. For this reason, radiography has limited applications for building and bridges, and is only generally used when site welding pipelines. However, it is a well-established technique which has the particular advantage of providing a permanent record, and when the health issues can be overcome, it is widely used to detect internal flaws in weldments and to check for hidden mis-assemblies. The permanent records are easier for the untrained engineer to assess than an ultrasonic inspection report that uses specialist language. The concerns about health and safety make it unlikely that an engineer will find radiography used on orthodox building and bridge structures.
9 WELDING DEFECTS, SIGNIFICANCE AND REPAIR

9.1 Imperfections or defects

In any weld detail there will be imperfections. However, it is important to be able to distinguish between a relatively minor imperfection that will not affect the fitness for purpose and a defect that will affect fitness for purpose. Thus a definition of defect could be:

A defect is an unacceptable imperfection that will prejudice its capacity to satisfy the designer’s expectations of it.

An imperfection is any variation from perfection in a weld.

To distinguish between imperfections and defects, acceptance criteria need to be defined, as mentioned in Section 8.1. The NSSS[18] provides a comprehensive specification that defines when imperfections should be classified as defects, and the remedial action necessary.

Defects, which may or may not always require repair, can be either volumetric defects i.e. defects that have length, width, and depth, or planar defects i.e. defects that have length and width only. Generally, planar defects are far more serious than they may first appear because even when small they can precipitate catastrophic brittle fracture.

For this reason, it is readily accepted that cracks and other welding defects should be treated very seriously. All defects can be repaired, but it may well prove very inconvenient and expensive to do so. However, when faced with a potentially very expensive and disruptive repair bill, it is important to pause and examine whether the defects do compromise the fitness for purpose of the weld. The advice of a welding engineer should be sought when considering the fitness for purpose of the weld. Similarly, before any remedial work commences, it is important to determine why the weld defect(s) occurred in the first place, to avoid simply repeating the problem.

9.2 Planar defects

The principal types of planar defects are tears, cracks and lack of fusion.

Tears

The types of planar defects that can occur in welding are:

Shrinkage tearing

This form of tearing occurs when the thermal contraction of the weld and surrounding hot metal leads to such high stresses that the weldment literally tears itself apart. These tears will obviously occur at the weakest point which may be on a small cold weld or in a large hot one which, because of its temperature, is providing only a fraction of its normal yield strength. Shrinkage tears may be short or long, and may or may not be adjacent to the weld that was being made at the time.
Lamellar tearing
Lamellar tearing occurs in the Heat Affected Zone (HAZ) of the parent material, and was for a long time the bane of the heavy constructional steelwork industry, especially the offshore sector. The occurrence of lamellar tearing has been much reduced by the introduction of cleaner steels with lower sulphur levels and by improvements to the steel making process. Tearing in the older steels arose because of weldment solidification developing through-thickness (Z direction) stresses. The steel rolling process had left the material unable to accommodate these through-thickness stresses. The potential for lamellar tearing arose from manganese sulphide contaminants in the steel, which the rolling process had converted into layers of overlapping pancake-shaped inclusions. Such inclusions have little strength and thus can tear apart if subjected to a through-thickness stress. This does not necessarily mean that material with sulphide inclusions is of otherwise poor quality, but might indicate inappropriate material selection for those joint configurations that produce through-thickness stresses.

Lamellar tearing is a cracking phenomenon that occurs beneath welds and can be found in rolled plate fabrication. The tearing always lies within the parent plate, parallel to the original material surface.

Most steelwork contractors have experienced lamellar tearing in plates in the range of 12-60 mm thickness, but the majority feel that there are few problems with plates below 25 mm. Only a small percentage of steel plates are susceptible to tearing. Lamellar tearing is similar to delamination but is not a close relative to it, despite a superficial similarity of names. A conventional ultrasonic check on material prior to fabrication will not detect whether a material is susceptible to lamellar tearing, only whether laminations are already present.

As repairs of lamellar tearing will include a large volume of the parent material as well as the weld itself they will be very expensive. Therefore it is essential to avoid lamellar tearing if at all possible and one of the ways of doing this is to select a material which can accommodate the through thickness tensile stresses which cause it. The most usual way to do this is to take a tensile test specimen in the through thickness direction of the plate and subject it to mechanical testing. Ductility is the important parameter that has to be measured and this is quoted as the Short Transverse Reduction in Area (STRA). The details of the test and ways of evaluating the results are described very thoroughly in BS EN 1011[8].

Generally, important steps in avoiding lamellar tearing are:

- Design welded connections to avoid through-thickness welding stresses.
- Use minimum throat dimension of welds and/or minimum weld volume consistent with design loads.
- Ensure that a material that needs to be subjected to high through thickness strains has been proved to be able to accommodate them.
- Ensure that NDT is able to detect lamellar tearing by considering inspection techniques at the same time as the connection is designed.

Remember that it is far cheaper to design to avoid these defects, than to repair them.
**Cracks**

The types of cracking found in constructional steelwork are solidification cracking and hydrogen cracking.

**Solidification cracking**

Solidification cracking is similar to shrinkage tearing inasmuch as it is associated with the thermal shrinkage of a weld as it cools. However, these defects are caused by the much higher volume changes that occur as the weld metal solidifies and therefore occur only in the weld metal. Solidification cracks are most often found at the point where the welder finishes a pass, in which case a modification of his technique can prevent further occurrence. Alternatively where these cracks occur along the length of a weld, known as centre line cracking, the fault may lie with the welding procedure or with ‘dirty’ steels (i.e. containing high levels of sulphur, phosphorus, silicon etc.) or contaminated materials.

**Hydrogen Cracking**

Hydrogen cracking, which may also be referred to as Heat Affected Zone (HAZ) cracking, is a defect, which can occur in either the parent plate or in the weld metal. Hydrogen Cracking occurs as either an individual crack or as a continuous series of cracks, along the full length of a weld. It is caused by only very small amounts of hydrogen absorbed into the weld metal from hydrogen in the atmosphere, or the welding consumable, or from contaminants on the metal. The hydrogen, now in its atomic rather than molecular form, will diffuse through the weld and parent metal until under the action of residual or applied stresses, it can lead to some cracking in steel microstructures. The methods for avoiding hydrogen cracking are given in Section 3.4.1 of this guide.

**Lack of fusion**

Lack of fusion is self-explanatory, and simply describes the situation when the weld metal is not fused to the parent metal. This is usually a problem associated with procedure or technique, and may necessitate a revised welding procedure specification.

### 9.3 Finding (all) the defects

If a crack is located, this should be taken as a strong indicator that other cracks may be present and these should be looked for. It is generally impossible to examine all welds completely, due to:

1. Difficult access
2. Poor connection design (usually NDT is not considered during design)
3. Limitations of the NDT equipment.

If a crack is detected and the weld repaired by removing it and re-welding the joint, there still exists a possibility that there may be other cracks present which have not been detected. Some additional inspection may be necessary to deal with this. When defects are detected, the weld should not simply be repaired and re-examined. The correct action is to find the cause of the defect(s) and put in hand corrective actions to the way in which the welding is being carried out. The extent and types of inspection should be increased to try and ensure that any further defects are found and repaired.
Welder induced defects will normally be less serious than procedural ones because they will be far less widespread and affect a few connections rather than the whole fabrication. Should the defect be due to, say, hydrogen cracking, a much more serious situation exits. In addition, it is very unlikely that it will have been restricted to one welder and a degree of additional inspection will be required along with an explanation for the occurrence.

9.4 Repair

The repair of welds will always be disruptive and often will also be expensive. In some cases the solution might simply lie with removal of the defective portion of the weld by grinding, air-arc or oxy-acetylene gouging and a replacing of weld metal according to the original procedure. Other less palatable solution could involve the removal of entire pieces of material, or even a whole section. In the case of lamellar tearing it may even require the rejection of a whole batch of steel.

However it should be noted that in certain cases, it may be beneficial not to repair a defect as the repair itself could lead to more serious problems; this is more often the case for volumetric defects and not normally with cracks.

Repair options should be considered individually for specific applications, with advice from a welding professional.

9.5 Summary

The important actions when serious defects are reported, are:

1. Identify both the nature and the cause of the defect.
2. Ensure action has been taken to prevent further occurrence of the defect (even if this requires stopping the welding operation in progress).
3. Consider the potential for further undetected defects.
4. Ensure corrective action is taken to both locate and repair all defects.
5. Use experts in structural analysis, welding engineering and fracture mechanics to determine if not repairing is a viable option.
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APPENDIX A  Glossary of terms

The reader is referred to the fuller glossary given in BS 499-1*.

Arc Energy
The amount of heat introduced by the welding process per unit length of weld, in kJ/mm.

Arcing
The accidental striking of an arc away from the weld and/or the damage on the parent metal resulting from the accidental striking of an arc away from the weld.

Back gouging
Removal of all or most of the first side root run by carbon arc gouging before depositing the root run on the second side to be welded.

Baking
Often used when MMA electrodes are dried at high temperatures, eg above about 250°C, to remove moisture.

Bead (Run, Pass)
Weld deposited during a single progression of an electrode.

Bead, stringer
Run of weld metal during a single progression of an electrode without weaving.

Bead, weave
Run of weld metal deposited with a transverse oscillatory motion.

Butt weld
Fusion weld between two members substantially in the same plane.

Buttering
One or more layers of weld metal laid as a surface on parent material to form a transition layer between that material and the weld filler metal.

Carbon equivalent (CE) value
A number, calculated from the chemical composition of the steel by an empirical formula as described in Section 3.4.1, indicating the steel’s susceptibility to hydrogen cracking and its hardenability.

Cored wire
A consumable electrode having a core of flux or other material.

Coupon plates (Production test plates)
Run-off plates, with the same profile as the production weld, attached to the end of that weld and welded continuously with it.

CO: welding
Metal arc welding where a bare wire electrode is used, and carbon dioxide used as the shielding gas.

Combined thickness
The sum of the thicknesses of the parent metal meeting at a joint. The thickness of each element is measured at 75 mm from the joint.

Cored wire
A wire consumable having an internal core of flux and/or other material.

Electrode, hydrogen controlled
A covered electrode that can produce less than a specific amount of hydrogen in the deposited weld metal.

Electrode, basic
A covered electrode whose flux coating is based on calcium carbonate and fluorspar.

Electrode, iron powder
A covered electrode the covering of which contains a proportion of iron powder.

Electrode positive (USA: Reverse polarity)
Direct current electrode positive (DCEP), workpiece negative for DC welding.

Electrode negative (USA: Straight polarity)
Direct current electrode negative (DCEN), workpiece positive.

Fillet weld
Fusion weld approximately triangular in shape joining two surfaces at an angle between them.

Fitup
The gap between the two faces of a joint immediately prior to welding.

Fusion welding
Welding between surfaces brought to a molten state without applied pressure.

Fusion face (Fusion zone)
Area of parent metal that is welded into the weld metal.

Gouging
Removal of metal by mechanical or arc methods, generally in the form of a groove.

Gouging, back
Removal of parent metal and weld metal from the other side of a root run(s) of a butt weld to achieve full weld metal penetration from that other side.

Hardenability
The tendency of a ferritic steel to produce a hard microstructure as a result of heating and rapid cooling (typically in the heat affected zone).
Heat affected zone (HAZ)
That part of the parent material immediately adjacent to the weld bead whose microstructure and mechanical properties have been changed due to the heat of the weld.

Heat input
The amount of heat supplied to the parent metal by welding. The heat results from the energy of the welding arc, reduced by the efficiency of the transfer of heat.

Lamellar tear
A stepped-like crack underneath welds, parallel to the fusion face and with the parent material.

Leg length
Distance from root of joint to toe of fillet weld.

MAG welding
Gas-shielded welding using a consumable wire electrode where the shielding gas is provided by a shroud of active or non-inert mixture of gases.

MIG welding
Gas-shielded welding using a consumable wire electrode where the shielding gas is provided by a shroud of inert gas.

Preheat temperature
The temperature of the joint immediately prior to welding, achieved by heating the parent metal.

Penetration
The depth that a weld bead extends into the parent metal.

Porosity
Holes or pores in a weld metal formed by gas evolved during solidification.

Prebend
To bend a component to an angle so that, when welded, the correct attitude of that component is obtained.

Preset
To set a component at an angle which attempts to predict the angular distortion so that after welding the correct alignment is obtained.

Residual stress
The stress remaining in a metal part as a result of welding. More generally, residual stresses also arise from cooling of the rolled member or plate, and from any post-rolling activities, such as straightening.

Restraint
The extent to which the parts to be welded are secured from moving during and after welding. If joints are restrained, the shrinkage of the cooling weld will inevitably lead to residual stresses.
Root joint
That part of a joint to be welded where the members of that joint are closest to each other.

Root pass
The first run of a multipass weld.

Sealing run
Final run on the root side of a weld.

Slag
Fused, non-metallic substance from welding process.

Spatter
Globules or particles of metal expelled during cutting or welding.

Tack weld
A short length of weld used to hold components together so that they can be welded.

TIG welding
Inert gas welding using a pure or activated tungsten electrode (which is not consumed). A separate consumable is introduced to the arc.

Toe
Boundary between weld surface of a fillet weld and parent metal.

Throat, weld
Shortest distance from root of fillet weld to its face.

Undercut
Irregular grooves at a toe of a run in the parent metal and not filled with weld metal.

Weld, automatic
Welding where all parameters such as travel, wire feed and arc control are performed automatically.

Weld, semi-automatic
Welding where wire feed is automatic but the advance of the welding is controlled manually.

Weldability
The ease with which a metal can be welded to give a joint free from unacceptable imperfections, particularly cracks, and having the required properties.

Weldment
An assembly, which is welded.
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