Sub-surface inspection of welds

No. 6.03

Scope

This Guidance Note applies to all welds in structural steelwork for bridges. It covers the sub-surface inspection of welds using ultrasonic inspection testing and radiographic inspection. Visual inspection and surface inspection are covered in GN 6.06 and 6.02 respectively.

Ultrasonic testing

Ultrasonic testing (frequently abbreviated to UT) uses ultrasound to detect sub-surface imperfections (also termed embedded discontinuities) in the weld and the parent metal. A soundwave transmitted through the steel by a surface mounted probe is reflected back by any boundary or intervening imperfection. A signal on the screen of the flaw detector shows the time the sound wave takes to travel from the far boundary; where an imperfection is present it shows the shorter time for the signal to travel back from the imperfection.

The amplitude of a reflected signal from a imperfection depends on the form of the imperfection, whether it is rounded or planar. An imperfection near to the probe will give a greater response than a imperfection of the same size further away. With planar imperfections such as cracks, lack of penetration and lack of sidewall fusion, the amplitude of the signal is related not only to the shape but also to its orientation and the nature of the reflecting surface. The angle of the probe to the imperfection has to be selected to obtain maximum response. Imperfections are measured and assessed against the limiting values and unacceptable imperfections are declared defects.

Ultrasonic testing is a portable and easily applied process, unlike radiography which is now little used in the industry due to health and safety concerns relating to radiation. The method has a sensitivity adequate for the normal range of thicknesses used in structural steelwork. It should not normally be used for plate thicknesses less than 8 mm. UT can detect the most common imperfections found in welding and can be sensitive to those that are too small to be detrimental to the soundness of the weld, whereas radiography may not detect certain types of imperfection or be capable of accurate sizing.

Ultrasonic testing may also be used on areas of plates where the designer has specified limits on laminar defects (see GN 3.02).

Radiographic inspection

Radiographic inspection, (also called radiography) uses a beam of penetrating ionizing radiation, usually from an X-ray or gamma-ray source, to detect sub-surface imperfections in the weld and the parent metal. In general, a gamma-ray technique will be less sensitive than an X-ray technique for penetrated thicknesses between 10 mm and 50 mm. A weldment in the path of a beam of penetrating ionizing radiation absorbs the radiation as it passes through the material. Any imperfection present will cause a difference in density of the material and thus the absorption in the imperfection area will differ from that in the surrounding area. This change in absorption is detected by placing a photographic film on the far side of the weldment from the radiation source. The photographic image produced by the beam of penetrating ionizing radiation is called a radiograph. The flaw detection capability of a radiographic technique increases as the graininess of the film is reduced and is also dependent on the film-screen combination.

Radiography has been used in cases of dispute to clarify the nature, sizes or extent of flaws detected ultrasonically. This may be required where UT gives indications of sub-surface imperfections. However, unless planar flaws are favourably oriented to the beam, the result may not necessarily be conclusive. Unlike the UK, in the USA and many other countries outside Europe, radiography is the preferred method for the detection of sub-surface flaws, primarily because the radiograph is seen as providing a permanent record of the evidence of the flaw which is readily understood even though interpretation is subjective.

Scope of inspection

The standard applicable to the execution of steel structures, including bridges, is EN 1090-2 (Ref 1). Workmanship, inspection and testing requirements are defined in that Standard according to the ‘execution class’. EN 1090-2 states that EXC3 could be specified for bridges and common practice supports this.

For new welding procedure specifications, a more stringent testing regime is applied to the first 5 joints tested to establish that the WPS produces conforming quality welds when implemented in production.

Visual examination is always required, followed by an amount of supplementary non-destructive testing described in EN 1090-2 Table 24. Table 23 in the Standard defines minimum hold times after welding before supplementary NDT takes place. The extent of testing for internal imperfections is given for various joint types and execution class.

The Standard also provides for the project specification to identify specific joints for inspection together with the extent and method of testing. This is to accommodate more stringent examination when fatigue strength requirements are higher.

Where partial inspection is specified, EN 1090-2 also states that sampling should cover as widely as possible, joint type, material grade, welding equipment and the work of the welders.

EN 1090-2 refers to the withdrawn standard EN 12062 (Ref 2) for the selection of methods of non-destructive testing, the selection of lengths to be tested where partial or percentage examination is specified and guidance on additional testing where non-acceptable indications are revealed. Although the reference to EN 12062 is a dated reference in EN 1090-2, the normative references within EN 12062 are undated and have all been superseded; therefore the latest editions of the replacement standards apply. EN 12062 is superseded by EN ISO 17635 (Ref 3) and reference to it is likely to be included in a future revision of EN 1090-2. The two standards are very similar in content and for clarity the guidance below refers to the later Standard.

For highway infrastructure projects, the Specification for Highway Works (SHW) Series 1800 was published in August 2014 (Ref 4). This specification interprets and implements PD 6705-2 (Ref 5) and introduces the concept of Quantified Service Category (QSC) to determine the method of non-destructive testing, frequency of testing and the acceptance levels which are different from those in EN 1090-2. See GN 6.01 for further comment. Appendix 18/1 should cover any project-specific requirements. It is incumbent on the Designer to determine the relevant QSC and communicate this through Appendix 18/1 or the drawings (see GN 2.12). The Designer should also avoid over-complicating the requirements and keep in mind that it is much easier for steelwork contractors to use one category for the project than use multiple different categories and run the risk of misunderstanding or misinterpretation.

Method of non-destructive testing

EN 1090-2 states that the method of NDT shall be selected from those described in EN ISO 17635. It suggests that radiography or ultrasonic testing are suitable methods for testing butt welds for internal imperfections. Knowledge of the weld preparation and size, and the most likely type of imperfection that the welding process may produce, is essential so that the correct examination methods are employed.

For bridges in conventional structural steels, UT using the pulse echo technique is the principal method in use by UK steelwork contractors.

EN ISO 17635 states that the ultrasonic pulse echo technique shall be carried out in accordance with EN ISO 17640 (Ref 6). For the Quality Level applicable to EXC3 joints described below, the examination technique and level shall be at least B in accordance with Annex A of EN ISO 17640 with characterization of indications where required in accordance with BS EN ISO 23279 (Ref 7).

Radiographic examination of welds should be carried out in accordance with one or more of the appropriate techniques given in EN ISO 17636 (Ref 8). The choice of radiographic technique should be defined by the specification.

For infrastructure projects carried out in accordance with the SHW Series 1800, the methods of testing are specified in Tables 18/4 and 18/6. The selection of method and frequency of testing is based upon the material thickness and the QSC. Table 18/5 provides a method of adjusting the frequency of test depending upon certain criteria, such as how and where the weld was made, the material grade, the QSC and whether the weld is under repair. For example, the proportion of supplementary NDT is adjusted down where there is less risk of imperfection because the weld was deposited using automatic or robotic processes, or adjusted up for higher grades of material, site welds or repair situations.

Acceptance criteria

EN 1090-2 requires that for EXC3 joints the acceptance criteria for weld imperfections shall be Quality Level B to EN ISO 5817 (Ref 9).

For joints where an enhanced level of quality is required to meet design fatigue strength requirements, EN 1090-2 Table 17 gives additional requirements for EXC4 as Quality Level B+. In addition, the Table also gives further supplementary requirements for bridge deck steelwork. These are more stringent acceptance standards for several imperfection types over and above Quality Level B.

Generally the requirements for Quality Level B+ are not practically achievable in routine production. Indeed, normal welding procedure and welder qualification tests are not assessed against acceptance criteria at this level. If a higher quality level is required, this should be specified for each relevant joint detail and the extent and method of testing can be selected to detect imperfections and to characterize them.

For highway infrastructure projects carried out in accordance with the SHW, the acceptance criteria are specified in Table 18/10, rather than in EN 1090-2, clause 7.6, and are based on the QSC.

EN 1090-2 suggests that non-conforming welds be judged individually and evaluation should be based on the function of the component and the characteristics of the defect in terms of type, size and location in order to determine acceptability. Reference back to the design codes may be used to support the evaluation.

The designer should be aware that internal imperfection types, such as sub-surface porosity and solid inclusions in small fillet welds are not detectable using specified examination techniques such as ultrasonic testing as used in bridgework. Table 24 applies supplementary NDT to transverse fillet welds in tension or shear and the frequency of test is varied depending upon the throat thickness and thickest material being joined. Standards do not prescribe a method for the examination of small fillet welds for sub-surface imperfections because the complexity and limitations of ultrasonic testing increase as the size of the fillet weld decreases. Most bridgework fillet welds are usually of less than 12 mm leg length, and are therefore too small to be tested using ultrasonic techniques.

SHW Table 18/4 does require partial ultrasonic testing for transverse fillets in higher grade (> S355) materials and / or site welded joints where the weld throat thickness is greater than 10 mm. There are also material thickness considerations and the Table should be studied carefully to ensure that specified requirements are understood. The advice of specialists should be sought if supplementary ultrasonic testing is required on fillet welds.

Repair

Where testing identifies defects, repair may become necessary. Sub-surface repairs should be reported through non-conformance and corrective action procedures. The repair is likely to involve gouging and welding and it is necessary to maintain control by implementing a repair procedure either of a generic nature or specifically developed to correct the problem. In either case, the completed repair area needs re-examination and reporting. Both EN ISO 17635 Annex C and SHW Table 18/5 provide guidelines or requirements respectively for examination or increased sampling to isolate and identify any recurring problems.

Non-destructive testing personnel

All inspection to ensure the quality of the completed welding should be carried out by appropriately qualified and experienced personnel as required by EN 3834-2 (Ref 10). Non-destructive testing, such as UT should be performed by personnel qualified in accordance with EN 473 (Ref 11) or the later EN ISO 9712 (Ref 12).

The successful application of manual ultrasonic testing depends on the knowledge and experience of the personnel responsible for producing the test procedures, and the competence and ability of the ultrasonic practitioner to carry out the procedural requirements and interpret the results.

The operator must be skilled in calibrating the flaw detector, able to recognize the significant characteristics of the echo-dynamic patterns of different types of imperfection, and be able to report the results for each weld examined.

Sub-surface defects
The most common types of sub-surface defects that can occur as a result of the welding process are:

- Sub surface porosity.
- Inclusions.
- Lack of fusion.
- Lamellar tears.
- Sub surface cracks.

Porosity (also termed gas cavities) is created when gas is entrapped in the solidifying weld metal, and is a sign that the welding process has not been properly controlled, or that the base metal is contaminated or of variable composition. The presence of porosity indicates that there is the possibility of hydrogen in the weld and heat affected zone (HAZ) that may lead to cracking. Sub-surface porosity may be a number of gas pores either uniformly distributed throughout the weld metal or in a cluster, a large elongated cavity with its major dimension aligned with the axis of the weld, or a cluster of worm holes (also known as piping porosity).

Inclusions are solid foreign substances entrapped in the weld metal. The foreign substance may be non-metallic slag, flux, metallic oxide, or copper. In general, slag inclusions result from faulty welding technique, failure to clean properly between welding passes, and conditions that lead to limited access for welding within the joint. Usually the molten slag will float to the top of the weld, but sharp notches in boundaries or between passes can cause slag to be entrapped under the molten weld metal. Metallic oxides result from welding over unclean steel or weld metal. If the electrode holder is dipped in the molten weld metal or if the current is set too high, droplets of copper may be transferred to the weld metal. Inclusions are detectable by UT and radiography.

Lack of fusion between weld metal and parent metal, or between weld metal and weld metal, may result from improper welding techniques or preparation of the metal for welding. Deficiencies causing lack of fusion (also termed incomplete fusion) include insufficient welding heat, improper electrode manipulation and lack of access to all boundaries that are to be fused during welding. Tightly adhering oxides may prevent complete fusion even when there is access and proper procedures are used. Lack of penetration (also termed incomplete penetration) is the lack of fusion between parent metal and parent metal due to failure of the weld metal to extend into the root of the joint. Lack of fusion is detectable by UT and sometimes by radiography.

Lamellar tears are planar separations in the base metal adjacent to the HAZ caused by thermally induced shrinkage stresses in the through thickness direction resulting from welding. Tears are generally parallel to the surface of rolled products, and the fracture usually propagates from one plane to another on shear planes normal to the rolled surface. Specification of steel of proven through thickness properties for cruciform, T and corner joints when the total weld throat on any one surface exceeds 35 mm for a T-joint or 25 mm for a corner joint should be considered to avoid this problem (see GN 3.02). Lamellar tears are detectable by UT but not by radiography.

Cracks occur in the weld and/or base metal when localized stresses exceed the ultimate strength of the material. Generally high residual stresses are present and crack initiation and propagation is greatly influenced by the presence of imperfections that concentrate stress. Hydrogen embrittlement is often a contributor to crack formation - see GN 6.04 for further guidance. Welding related cracks are generally brittle in nature, exhibiting little plastic deformation at the crack boundaries. Cracks are not detectable by radiography, unless very large.

Longitudinal cracks are parallel to the axis of the weld. They can be:

- throat cracks (otherwise known as centre-line or solidification cracks); these are generally found in the centre of the weld bead and are usually, but not always, hot cracks, formed on the solidification of the weld metal at temperatures near the melting point;
- root cracks; these are generally hot cracks in the root of the weld;
- toe cracks, propagating into the base metal from the toe of the weld where restraint stresses are highest; these are cold cracks forming hours or days after the completion of welding;
- hydrogen-induced heat affected zone cracks; these are cold cracks, generally short, although they may join to form larger continuous cracks, which align themselves with weld boundaries that concentrate residual stress.

In submerged arc welds made using the semi- or fully automatic welding process, longitudinal cracks are often associated with high welding speeds. In small welds between heavy sections, longitudinal cracks often result from fast cooling rates and high restraint.

Transverse cracks are orthogonal to the axis of the weld. They occur in the weld metal, the base metal or both. Transverse cracks initiating in the weld metal are commonly the result of longitudinal shrinkage stresses acting on excessively hard weld metal. Transverse cracks initiating in the HAZ are generally hydrogen cracks.

For further information on imperfections in metallic fusion welds, reference should be made to EN ISO 6520 (Ref 13).

References

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6. EN ISO 17640: 2010 Non-destructive testing of welds. Ultrasonic testing. Techniques, testing levels and assessment.
7. EN ISO 23279: 2010 Non-destructive testing of welds. Ultrasonic testing. Characterization of indications in welds.
8. EN ISO 17636-1: 2013 Non-destructive testing of welds. Radiographic testing. X- and gamma-ray techniques with film.
9. EN ISO 5817: 2014 Welding. Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded). Quality levels for imperfections.
10. EN ISO 3834-2: 2005 Quality requirements for fusion welding of metallic materials. Part 2: Comprehensive quality requirements.
11. EN 473: 2008 Non-destructive testing – Qualification and certification of NDT personnel – General principles. *Superseded*, *withdrawn.*
12. EN ISO 9712: 2012 Non-destructive testing. Qualification and certification of NDT personnel.
13. EN ISO 6520-1: 2007 Welding and allied processes. Classification of geometric imperfections in metallic materials. Fusion welding.