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Recommendations for repairs of welds

1.0 Introduction

This document provides general recommendations and guidelines for the repair of welds and the inspection of weld repairs during or following fabrication or construction.

These recommendations are based upon extensive practical experience and satisfactory application, with some experimental research and study.

It is generally agreed that the presence of discontinuities in welded joints is unavoidable. From this recognition, however, arises a problem of defining what is acceptable and what is not. The conventional acceptance standards for weld discontinuities in the existing codes or standards for welding were, by necessity, established arbitrarily and were closely related to:

(i) achievable standards of good workmanship
(ii) the detection capability of available inspection methods, and
(iii) supporting evidence of satisfactory performance in service.

In the absence of any knowledge of the engineering significance of weld discontinuities, these acceptance criteria were formulated without any direct relation to their effects on structural integrity. However, extensive research of recent years has explored the significance of weld discontinuities on the service performance of welded structures and, through the fitness for purpose approach, has provided workable means of assessing the need for repairs with full consideration of their cost and effective benefits in terms of structural integrity.

Because the primary concern must be with structural integrity, followed closely by the economic viability of the cost of repairs (both direct and hidden), one cannot dismiss the potential loss of structural integrity caused by inappropriate repairs.

The following problems may be associated with repairs of welds:

(i) incomplete removal of defect being repaired,
(ii) introduction of further discontinuities associated with the repair that may be more harmful and less readily detectable than the original defect,
(iii) degradation of material mechanical properties (strength, ductility, notch toughness) or microstructure, and
(iv) increased residual stress and distortion.

Engineering and cost considerations should contribute to any decision to undertake a repair. The direct cost of weld repairs and re-repairs (grinding, gouging, welding, supervision, inspection, etc.) will be significantly increased by hidden costs (loss of production space and time, penalty clauses, delays in shipment and deliveries, etc.), and may represent a considerable proportion of the overall cost of the structure.

The cost of weld repair will increase more significantly with the increase in the depth of the discontinuities within the thickness of material than with the length of the discontinuity. The severity of weld quality acceptance standards has a very significant influence on the cost of repairs. However, when repairs are found necessary, the problems particular to them must be fully understood and considered if the original quality of the weld is to be restored.

Because the probability of reduced structural integrity by repair welding cannot be dismissed, the decision whether repairs are necessary or not assumes special significance. Better understanding of the structural significance of discontinuities will greatly assist in this decision and provide backup resource material justifying the elimination of a great majority of repairs. However, when repairs are found necessary, the problems particular to them must be fully understood and considered if the original quality of the welds is to be restored.

The provisions in this document are intended to assist in drawing attention to the important aspects of repair and to provide operational guidance for their execution.

2.0 Definitions

Buttering: a surfacing variation in which surfacing metal is deposited on one or more surfaces to achieve the required dimensions.

Critical repairs (see Section 5): repairs on welded joints requiring:

(1) direct design intervention and/or

(2) refined procedural attention and stricter quality control in fabrication.

This category of repairs is more likely to occur under fatigue or brittle fracture and/or some specific stress conditions, and includes elements whose integrity, in the judgement of the designer, cannot be compromised from the standpoint of reliable and safe performance of the element or the structure in service.

Engineer: the professionally qualified designated representative of the regulatory authority or of the purchaser, as applicable.

Fracture critical members (FCM): members, including attachments, in a single load path structure that are subject to tensile stress and whose failure could lead to collapse of the structure.

National standard: the standard of any individual country having full contractual or jurisdictional authority over any specific action or operation to which a particular reference is made in the document.

Non-critical repairs (see Section 4): repairs outside the scope of the definition for critical repairs.

Weld defect: a weld discontinuity or group of discontinuities, which by nature or accumulated effect, with a size and/or density that exceeds the applicable acceptance criteria set by the pertinent specification or national standard, and hence is subject to rejection and repair.

Weld discontinuity: irregularities in the body of the weld or on the weld surface, such as a lack of homogeneity in the mechanical or metallurgical or physical characteristics of the material or weldment.

Weld imperfection: weld discontinuities that are within the acceptance criteria set by the pertinent specification or national standard, and are considered to have no practical limitations on the intended use of the product. Weld imperfections may be left without repair.

3.0 General considerations

3.1 *Basic types of repairs*

There are two fundamental conditions requiring weld repair:

(a) Welded joints rejected during inspection and/or mechanical testing as not meeting the applicable standards of acceptance. In most cases they will be fabrication shop repairs or repairs performed prior to the fabricated element or product being put in service.

(b) Welds or elements of welded steel structures which were rendered unable to continue to perform their designated service function due to either:
    (i) change in service conditions, or
    (ii) damage or failure.
    The required repair will be an on-site operation with the structure most likely subject to some loading condition.

3.2 *Need to establish cause*

Before undertaking repairs, it is desirable, and strongly recommended engineering practice, to establish the cause of the initial defect or failure. An investigation into the cause may yield important indications of potential repair problems. It may serve to prove the inadequacy of the original procedures and provide more enlightening data for corrective action. A good understanding of the cause of the defect or of the cause of failure is a prerequisite of a successful repair procedure. Welds containing cracks should not be repaired until the reason for the cracking has been determined.

The investigation of the causes for defects and, more importantly, the primary cause of a failure must be sufficiently comprehensive and thorough to permit the preparation of recommendations for preventing similar incidents in the future.

The following list of probable causes for defects in welds or causes of failures, not meeting actual service requirements, is offered to provide effective guidance:

(a) Joint design
    (i) inaccurate loading assumption
    (ii) inadequate method of analysis
    (iii) lack of full consideration of all applicable forces or their components
    (iv) difficulty in carrying out welding (access, edge distances) and inspection

(b) Material selection and controls
    (i) improper selection of filler metal for given material
    (ii) improper storage and control of filler metals, fluxes and shielding gasses
    (iii) environmental service conditions not anticipated in design

(c) Welding procedures and workmanship
    (i) improper joint condition and fit-up
    (ii) improper or inadequately detailed welding procedure specification
    (iii) improper weld size
    (iv) inadequate preheat or failure to maintain interpass temperature
    (v) inadequate postheat or failure to postheat
    (vi) poor workmanship or technique on the part of the welder or welding operator (or a lack of welding supervision)

3.3 *Investigation of damage or failures*

Specifically in the case of damage or service failures, the principal stages of investigation should include most of the following, as applicable:

(a) collection of background data and selection of samples

(b) preliminary examination of the failed part (visual examination and record-keeping)

(c) nondestructive testing

(d) mechanical testing (including hardness and toughness testing)

(e) selection, identification, preservation and/or cleaning of all specimens

(f) macroscopic examination and analysis (fracture surfaces, secondary cracks and other surface phenomena)

(g) microscopic examination and analysis

(h) selection and preparation of metallographic sections

(i) examination and analysis of metallographic sections

(j) determination of failure mechanism

(k) chemical analysis (comprehensive bulk, local, surface corrosion products, deposits of coatings, and microprobe analysis)

(l) analysis using fracture mechanics

(m) testing under simulated service conditions (special tests)

(n) analysis of all the evidence, formulation of conclusions and preparation of the report (including recommendations).

3.4 *Documentation*

It is recommended that:

(a) repair procedures referred to in Section 4 as non-critical should adequately describe the deficiency and the proposed method of repair. Critical repair procedures referred to in Section 5 should, in addition, include the location of the discontinuity within the joint and the member.

(b) in cases of in-service failures and repairs to fracture critical members, sketches or

drawings of repairs should show the discontinuity in plan view, elevation and section as necessary to adequately describe the discontinuity as it appears before repair. The repair sketches or drawings should be revised, if necessary, at the completion of repairs to document differences between the presumed initial type, size, orientation, and location of the unacceptable discontinuity and the final complete description of the unacceptable discontinuity as observed and measured during repair.

3.5 *Procedural recommendations*

It is recommended that:

(a) comprehensive repair procedures be prepared by the contractor for approval by the engineer or other authority having jurisdiction.

(b) repair procedures include the provisions shown in Sections 4 and 5 and list them in the order in which they are specified to be performed.

(c) repair welding in the same area may be performed twice. Following two repair attempts, subsequent repairs should be evaluated prior to initiation of the repair attempt.

4.0 Non-critical repairs

4.1 *Pre-approved repair procedures*

The contractor should prepare repair procedures for non-critical repairs and submit them to the engineer for pre-approval. These procedures pertain primarily to repairs of discontinuities identified during in-process fabrication. Pre-approved procedures may be employed after the inspector has verified that the discontinuity to be repaired is as described in the pre-approved procedure. Repair procedures which may be pre-approved include the following:

(a) repair of weld defects requiring excavation of weld material and/or base metal, including:
    (i) weld metal and base metal cracks, except in structural elements subject to fatigue loading or carrying primary tensile stress
    (ii) incomplete fusion of weld to base metal or between weld passes
    (iii) excessive slag inclusions to an unacceptable degree
    (iv) excessive porosity
    (v) reduction of excessive weld convexity, reinforcement or overlap.

(b) repair welding which consists solely of the deposition of additional weld metal, including:
    (i) insufficient weld throat or fillet weld leg
    (ii) excessive concavity
    (iii) excessive base metal undercut
    (iv) filling of weld craters.

(c) repair welding (buttering) to compensate for a root opening wider than that permitted, or a groove angle in excess of that permitted.

(d) base metal laminations detected during weld joint preparation.

(e) any correction by welding to compensate for a fabrication error, such as improper cutting, punching, drilling, machining, fitting, assembly, etc., except for structural elements subject to fatigue loading or carrying primary tensile stress.

(f) dimensional corrections (including improperly placed detail material) requiring weld removal and rewelding, except those structural elements subject to fatigue loading or carrying primary tensile stress.

4.2 *Repair Procedure Recommendations*

(a) It is recommended that the following defects as identified under 4.1(a) and (b) be corrected in the following manner:

overlap excessive convexity	reduce by removal of excess weld metal
excessive concavity of weld excessive convavity of crater undersize welds undercutting	clean and deposit additional weld metal
excessive weld porosity slag inclusions incomplete fusion	remove defective portions and reweld
crater cracks	remove by grinding, followed by dye penetrant or magnetic particle testing or other positive means, and reweld
cracks in weld, other than crater cracks cracks in base metal	ascertain the extent of the crack by use of dye penetrant or magnetic particle examination or other positive means, remove the crack and reweld
welds of insufficient strength, ductility or notch toughness	completely remove the weld and reweld

(b) When weld defects are removed by grinding only, the final weld surface and the transition to the base material should be smooth.

(c) When a weldment has failed radiographic inspection, an ultrasonic examination prior to gouging is advisable in order to accurately locate the discontinuity. This is of special economic significance on the case of thick members as it determines the side on which the excavation will be shallower.

(d) Before repair welding of cracks, the defect should be completely removed. The excavated area should have smooth transitions to the base metal surface and allow good access for both pre-repair welding nondestructive examination (NDE) after excavation and for subsequent repair welding. The excavated groove should be minimum 50 mm long, measured at defect depth, even if the defect itself is smaller. Defects spaced less than 100 mm should be repaired as one continuous defect.

(e) After excavation, complete removal of the defect should be confirmed by use of dye penetrant examination, magnetic particle testing or other positive means. Post weld heat treatment (PWHT) should be performed after repair, if specified for the original

weld.

(f) The repair procedures should include the applicable welding procedure specification (WPS). If the WPS was approved by the authority having jurisdiction prior to construction, it need not be qualified by test for the specific method of repair unless a change in essential variables has been made or unless otherwise required by the engineer. Repair and re-repair welding may be performed using the same WPS as for the original weld, or a separately qualified procedure. Any welding and/or rewelding should be done using approved WPSs including preheat, interpass temperature or heat input levels as required, and including any postheating or post-weld heat treatment, if specified.

(g) If the geometry of the repair joint or of the excavation is similar to the geometry of a prequalified joint preparation as defined in an applicable national standard, and permits good access to all portions of the joint or excavation during the proposed sequence of welding, it should not require qualification by test unless required by the engineer.

(h) Any additional weld metal to be placed to compensate for any deficiency in size should be deposited using an electrode preferably smaller than that used to make the original weld, but not less than 3.2 mm in diameter for shielded metal arc welding (manual metal arc welding) and 0.9 mm for gas metal arc welding processes.

(i) Faces of weld repair areas should have at least the same surface quality and finish, if required, and should be blended to the same contour and throat dimension as the original sound weld.

(j) After repair welding, the entire repaired or replaced weld, and an area plus at least 100 mm on each side of the repaired area, should be subjected at least to the same NDE as specified for the original weld, or as specified by the engineer, with the same quality acceptance criteria applicable.

(k) If applicable, the remaining thickness in the ground area shall be measured. The thickness of base metal removed by grinding shall not be reduced to less than 95% of the nominal base metal thickness, nor more than 3 mm. Similarly, the throat of complete joint penetration groove welds shall not be reduced to less than 95% of the nominal base metal thickness, nor more than 3 mm. Repair welding is required if the remaining thickness is less than that specified.

(l) Parts distorted by welding beyond specified tolerances should be straightened by mechanical means or by carefully supervised application of a limited amount of localized heat. The temperature of the heated areas should not exceed 600°C for quenched and tempered steel, nor 650°C for other steels. Temperatures should be measured using temperature indicating crayons, surface temperature thermometers, or equally positive means. Unless mechanical straightening methods are used in conjunction with the application of heat, the part to be heated for straightening should be substantially free of stress and from external forces.

(m) To restore mislocated or unacceptable holes, place steel backing of the same material specification as the base metal at a depth of approximately one-half the thickness of the member, gouge an elongated boat-shaped cavity down to the backing, then fill the cavity by welding using the stringer bead technique. After the first side is welded, gouge another elongated boat-shaped cavity on the second side, completely removing the temporary backing, and fill the second side cavity by welding using the stringer bead technique.

4.3 *Recommended limits to pre-approved weld repairs*

It is recommended that weld repairs using pre-approved repair procedures be limited to the following criteria:

(a) Buttering not greater than twice the thickness of the thinner part or 20 mm, whichever is less

(b) Filling of gouges in cut edges not more than 10 mm in depth

(c) Laminar discontinuities at weld joint preparation not exceeding 25 mm in depth, or one-half the thickness of the cut edge, whichever is less, provided the discontinuity is not within 300 mm of a butt joint loaded in tension. Repair shall be made by excavating from the cut edge.

(d) First-time excavation and repair from one side of groove welds and fillet welds which contain unacceptable porosity, slag and fusion discontinuities, provided the excavations do not exceed the following limits:

Length of Weld “L”	Length of Excavation
Up to 0.5 m	L or 250 mm, whichever is less
Over 0.5 m to 1.0 m	300 mm
Over 1.0 m to 2.0 m	450 mm
Over 2.0 m to 4.0 m	600 mm
Over 4.0 m to 8.0 m	900 mm
Over 8.0 m	900 mm or 10% L, whichever is greater

(e) Groove weld excavations not exceeding 65 percent of the weld size shown on the drawings

(f) Repairs to cracks of root passes only if the crack is discovered and corrected before depositing subsequent weld passes

(g) Deposition of additional weld metal up to 10 mm deep, or 1/4 the base-metal thickness, whichever is less, to correct for weld length or joint geometry

4.4 *Contractor option*

For non-critical repairs, the contractor should have the option of repairing the unacceptable weld, removing and replacing the entire weld, or removing and replacing the entire assembly.

5.0 Critical repairs

Weld repairs beyond those designated in Section 4 are considered *critical repairs*. For *fracture critical members* (FCM), repair procedures should be individually approved by the engineer before repair activities are started. For critical repairs on other than fracture critical members (FCM), the engineer may agree to other arrangements proposed by the contractor to minimize interference with production. In either case, the repair procedures shall include welding procedures approved by the engineer or authority having jurisdiction.

Critical repairs include the following:

(a) Repair of lamellar tearing

(b) Repair of any delayed cracks in weld or base metal

(c) Repair of electroslag or electrogas welds with internal defects;

(d) For structural elements subject to fatigue loading or carrying primary tensile stress:
  (i) weld metal or base metal cracks
  (ii) any correction by welding to compensate for a fabrication error, such as improper cutting, punching, drilling, machining, fitting, assembly, etc.
  (iii) dimensional corrections (including improperly placed detail material) requiring weld removal and rewelding
  (iv) repair of laminar discontinuities exceeding the limits of 4.3(c)

(e) For fracture critical members, any repair exceeding the limits of 4.3

5.1 *Repair procedure recommendations*

Weld repair procedures should include those items described in 4.2, as modified and supplemented by the following provisions:

(a) Surfaces should be cleaned and/or ground as necessary to aid visual and nondestructive examination (NDE) to enable the contractor and inspector to identify and quantify the discontinuity(s).

(b) In conformity with 3.4(a) and (b), the discontinuity should be shown in a drawing in size and location established on the basis of visual inspection and NDE. The location of the discontinuity and the repair area should be placed on the member or alongside the weld.

(c) The removal of weld metal or portions of the base metal may be done by machining, air carbon-arc cutting, air carbon-arc gouging, thermal cutting, chipping, or grinding. It should be done in such a manner that the remaining weld metal or base metal is not nicked or undercut. Unacceptable portions of the weld should be removed without substantial removal of the base metal.

(d) Procedures for air carbon-arc gouging, if used, should be completely described, including the sequence of progressive excavations and the preheating temperature prior to air carbon-arc gouging, if required. For material thickness exceeding 40 mm, preheat for gouging should not be less than 65°C.

(e) When accessible, air carbon-arc gouged and thermal cut surfaces that form a boundary for a repair weld should be ground to form a smooth, bright metal surface. Oxygen gouging should not be used.

(f) Magnetic particle or dye-penetrant examination, or other NDE method(s) approved by the engineer should be used to verify that the discontinuity has been removed, and that the extent of the discontinuity needing repair does not extend beyond that previously detected and planned for repair.

(g) Weld tabs, where required, and backing, when used, should be shown in detail.

(h) Single pass surface weld repairs should have a minimum length of 50 mm. Other weld repairs should have a minimum length of 100 mm. If repair welds to be placed are less than 100 mm apart, measured end to end, they should be linked into a single repair weld.

(i) The minimum preheat and interpass temperature required by the national standard governing the work should be increased to take into consideration the added restraint of the weldment. The preheat and interpass temperature should be at least 50°C above that specified for production welding, and a minimum of 150°C for repair welds other than surface welds. For quenched and tempered steels, care should be taken to ensure that the combined preheat or interpass temperature plus welding heat input does not exceed the steel manufacturer's recommendations. Localized repairs should be treated as having high restraint when a preheat calculation is used.

(j) When notch toughness of carbon and low-alloy constructional steels is a consideration, the maximum preheat and interpass temperature should not exceed 300°C. The maximum preheat and interpass temperature for quenched and tempered steels should not exceed that recommended by the steel manufacturer.

(k) Preheat and interpass temperatures should be maintained without interruption until the repair is completed.

(l) Inspection and NDE requirements for repairs should be identical to those originally applied to detect the weld defects, and should include the weld metal and fusion faces within 100 mm of the repair in all directions.

(m) Peening may be used to prevent cracking and lamellar tears by mechanically reducing residual stresses created by welding. Peening, when part of the repair procedure, should be completely described. To prevent sharp impressions, peening should be performed by mechanically striking convex surfaces of intermediate weld beads or layers with a round tool with a radius of approximately 6 mm. Peening energy should be sufficient to mechanically elongate the surface of the weld without creating overlapping or cracking. Pneumatic tools should be operated in a manner that prevents contamination of the weld by moisture, oil, or other materials. Care should be taken to avoid striking fusion boundaries or the base metal. Root and final passes should not be peened, except final passes that contain excess weld metal may be peened, provided all of the excess weld metal and all peening marks are subsequently removed by grinding. Peening should be done when the weld is at a temperature between 65°C and 260°C.

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(n) Application of postheat is recommended, and when used, should continue without interruption from the completion of repair welding to the end of the minimum specified postheat period. Postheat procedures may include minimum and maximum temperatures and specified rates of temperature reduction, if any.

(o) Except for brief periods required for heat curving, cambering and straightening, any heating of welds or base metal by sources other than the welding arc to temperatures in excess of 500°C is considered post weld heat treatment (PWHT). PWHT, if used, shall

be completely described in the repair procedure giving details of minimum and maximum temperature, maximum heating and cooling rates, minimum and maximum time at specified temperatures, and all other details necessary to control the heat treatment. Tests should be performed to determine the effects of the proposed heat treatment procedure on the strength, ductility, and notch toughness of welds and base metal before PWHT. The engineer may accept records of previous tests in lieu of specific testing for the designated repair. Visual inspection and NDE, when required, should be repeated or performed after the weldment has cooled to ambient temperature. Repairs to welds made in PWHT joints, after completion of PWHT, shall require new PWHT after repair.

(q) Repairs of groove welds in butt, tee and corner joints should be examined by ultrasonic testing (UT). Repairs in butt joints may also be examined using radiographic testing (RT). Fillet weld repairs should be examined by magnetic particle (MT) or dye penetrant (PT) methods. UT, RT, MT and PT procedures should conform to the requirements of the pertinent national standard. NDE may be performed as soon as the weldment has cooled to ambient temperature after an elapsed time indicated as follows:

	MT or PT	UT or RT
	groove welds not in tension fillet welds	groove welds in tension
$t < 50$ mm	24 hours	24 hours
$t \geq 50$ mm		48 hours

6.0 Inspection recommendations

Inspection and nondestructive examination should be a described in Sections 4 and 5, as applicable. The extent of inspection of welding repairs and the applicable standards of acceptance should be in accordance with the original contract documents or as specified by the engineer. All weld repair procedures should be made available to the inspector. The contractor should maintain documentation of all visual inspections and NDE and keep the pertinent records accessible to the engineer and to any other person designated by the engineer.