Fatigue quality of welded details

Scope

This Guidance Note describes the consequences on specification of weld quality as a result of the design stress range due to fatigue loading. It makes reference to the notion of Quantified Service Category (QSC) that is introduced in PD 6705-2 [1] and implemented by the Specification for Highway Works, Series 1800 [2].

Non-welded details are not covered in this Guidance Note, as the quality requirements are not affected by the QSC classification.

Introduction

In the design for fatigue according to BS EN 1993-1-9 [3], fatigue resistance of a range of steelwork details is defined in a series of tables (Tables 8.1 to 8.10). These 'detail categories' define the characteristic value of fatigue endurance for each detail, taking into account the effects of geometry and imperfections. Requirements for execution are described for some of the details in the tables but no reference is made to Execution Class or to the quality requirements (the extent of inspection and the acceptance criteria) in BS EN 1090-2 [4].

BS EN 1090-2 does define the extent of 'supplementary NDT' in relation to Execution Class for a limited number of types of weld but these do not reflect the wider range of details in BS EN 1993-1-9 or the design fatigue stress range. Acceptance criteria are defined simply in relation to a 'quality level' according to BS EN ISO 5817 [5].

The BSI committee responsible for the implementation of BS EN 1993-2 (B/525/10), through its UK National Annex, considered that the link between design requirements and execution quality was inadequately expressed by the two documents, BS EN 1090-2 and BS EN 1993-1-9; it therefore published a guidance document, PD 6705-2, that gave more detailed execution requirements, related to the design requirements for fatigue. It achieved this by introducing numbered 'quantified service categories' (QSC), enumerated as, for example, F56, with the number corresponding to the reference value of fatigue strength at 2 million cycles – i.e. the same numbering as for detail categories in BS EN 1993-1-9.

PD 6705-2 introduced the QSC concept after advocating that the level of QSC for any detail should be specified only sufficient for the design stress range at the detail. Thus, for example, a transverse double-sided butt weld in a flange might only need to be specified as F56, even though the detail category according to Table 8.3 of BS EN 1993-1-9 classifies this as detail category 90. The intention was to achieve economy by making the execution requirements for welds no greater than just sufficient for the calculated design stress range. The SHW 1800 series specifies the use of these QSC.

To respond to the SHW specification requirements, this Guidance Note offers designers some advice on the QSC levels to be specified and when it might be more economic to modify the detail to reduce the design stress range, rather than use a higher QSC requirement.

QSC levels

PD 6705-2 and the SHW 1800 series specification considers six levels of QSC, designated F36, F56, F71, F90, F112 and F140 in increasing severity of quality requirement. PD 6705-2 recommends F36 is not specified and F56 is recommended minimum QSC level. However, the free edge surfaces of transverse web stiffeners and attachments for bracing should be specified as F36, to avoid the fabricators needing to check plasma-cut edges for hardness and/or grind them at stress-raising features (as permitted by SHW 1806.4.4(2)).

Where possible, this choice should be discussed with the fabricator as it may influence the design or fabrication procedures.

Designing and specifying a single QSC each detail category for the whole bridge structure to suit the most onerous requirement anywhere in the bridge may minimize design effort, but could result in increased cost and time for execution and inspection as there is likely to be a higher incidence of non-conformances and repair, particularly if there happens to be just a single location where a high QSC is needed.

Alternatively, the QSC may be specified separately for each detail. This approach requires careful communication of the QSC, which could result in extra cost, delay and increased risk of error in designation.

The procedure recommend in PD 6705-2 is a compromise between the two approaches described. A QSC appropriate for the majority of the details is specified as the default minimum QSC for all detail categories and only the details requiring a more severe requirement are identified and given a higher QSC.

It is important to differentiate between the QSC information provided that relates to the execution quality of the welded details only and BS EN 1993-1-9 detail category used in the structural verification. While limiting the design stresses to a single specific QSC may be appropriate for many details and thereby reduce the execution and inspection effort, in the verification of the structure the design stress range for a given detail must not exceed that for the BS EN 1993-1-9 detail category. For example, a QSC level of F56 may be specified as the default minimum for a structure which defines the execution and inspection requirements. However, when the structure is designed, any detail whose BS EN 1993-1-9 detail category is less than 56, such as at the end of a cover plate welded to a flange (commonly referred to as a doubler plate) and whose BS EN 1993-1-9 detail category could be less than 56, the value for the BS EN 1993-1-9 detail category must be considered in the fatigue verification for this detail.

A method of specifying the QSC on drawings is included on PD6705-2.

Economy

To achieve the target safety levels assumed in BS EN 1993 economically, the designer must specify the minimum default QSC for the majority of the details and for details where a QSC higher than the minimum default QSC is required, specify the minimum QSCs for these.

In some cases it may be more economical to modify the detail to reduce the design stress range, rather than use a higher QSC requirement.

Example of a transverse stiffener welded to a main girder flange

Consider the following example where transverse stiffeners are welded to a main girder flange. The welded attachment is a category 80 detail in BS EN 1993-1-9, i.e. the reference value of the fatigue strength at 2 million cycles, $\Delta\sigma_c$, is 80 N/mm^2. The designer must verify that the equivalent constant amplitude fatigue stress range related to 2 million cycles, $\Delta\sigma_{E,2}$ in the flange is less than $\Delta\sigma_c$ (partial factors omitted in this discussion) Assuming the flange fatigue stress is verified, the designer could specify the QSC nearest to, but not below, F80 for the detail or if there are no more onerous details, for the whole structure. The nearest QSC is F90.

The SHW Series 1800 Table 18/6 states the supplementary NDT of shop welds in steel grades up to and including S355. For F90, where the flange plate thickness exceeds 20 mm and the transverse stiffener is attached with a 10 mm throat fillet weld, 100% of the joints shall receive magnetic particle or penetrant testing and 20% shall receive ultrasonic (UT) testing. (Note that the ultrasonic testing requirements in PD 6705-2 Table 6 differs in some cases from SHW Series 1800 Table 18/6. In this case the requirements of SHW Series 1800 Table 18/6 should apply, and shall apply where use of the SHW is a contractual requirement.). Although the testing regime is not especially onerous, undertaking more tests is likely to mean that more defects will be identified and more repairs will be required.

When the fatigue limit state governs the main girder design, as the case may be for a short span railway bridge, the designer can easily reduce the supplementary NDT by specifying a larger flange plate to reduce the flange fatigue stress range and thus require a lower QSC. In this example, if the flange plate were thickened (or a cover plate (doubler plate) added) and F56 justified, the percentage of joints requiring magnetic particle or penetrant testing would reduce to 10% and the requirement for ultrasonic testing would be eliminated.

Example of a transverse butt weld in a main girder flange

An even more obvious example of how a designer can improve the economy of a design is in the choice of the QSC specified for transverse butt welds. The detail category in BS EN 1993-1-9 for a butt weld, welded from both sides, is 80, i.e. the reference value of the fatigue strength at 2 million cycles, $\Delta\sigma_c$ is 80 N/mm^2. If the location of a joint is subject to high fatigue loads, the designer could specify that the joint is welded from both sides and the weld ground flush. This would increase the BS EN 1993-1-9 detail category to 112, i.e. the reference value of the fatigue strength at 2 million cycles $\Delta\sigma_c$ would be 112 N/mm^2 and the QSC for the detail can be specified as F112.

Although grinding should be minimized on health and safety grounds, in this example the fabrication effort to grind the weld in order to verify the detail for the higher stress range leads to moderate additional cost for grinding. However, fabrication costs are increased much more significantly by the more extensive supplementary NDT and likely increase in repairs.

These extra costs arise because the SHW Series 1800, Table 18/6, requires that joints specified QSC F112 made from plate thicker than 20 mm shall be subject to 100% magnetic particle or penetrant testing, 100% ultrasonic testing and 50% radiographic testing.

Radiographic testing is a particularly complicated, specialist and expensive procedure that also demands stringent health and safety controls. Designers should therefore only specify details requiring radiographic testing in extreme situations and must justify this in their CDM designer's risk assessments. However, the precautions and costs effectively prohibit the use of radiographic testing for bridgework. A phased array UT (PAUT) technique is an alternative to UT and radiographic testing permitted in SHW Series 1800 Table 18/6 and PD 6705-2 Table 6. Where the phased array UT is used instead of UT, radiographic testing can be avoided.

The acceptance criteria for the weld visual inspections for F112 are also more onerous and an increase in expensive repair quantity is likely.

In the event that the designer specified QSC F112 for such details generally in the structure, the impact on cost would be excessive, as it is unlikely that details in other locations would require such a high QSC: without the fabricator being informed otherwise, all such details would be subjected to the same level of NDT and onerous acceptance criteria.

Practical requirements for QSC in highway and railway bridges

The fatigue stress ranges in a bridge vary according to the type of structure and the location of the detail within the structure. The tables at the end of this Note summarize the ranges found in typical bridges.

References

[1] PD 6705-2:2020 Structural use of steel and aluminium. Part 2: Recommendations for the execution of steel bridges to BS EN 1090-2 - Guide

[2] Manual of contract documents for highway works. Volume 1 Specification for highway works. Series 1800 Structural steelwork. April 2021.

[3] BS EN 1993-1-9:2005. Eurocode 3. Design of steel structures. Fatigue.

[4] BS EN 1090-2:2018+A1:2024 Execution of steel structures and aluminium structures. Part 2: Technical requirements for steel structures.

[5] BS EN ISO 5817:2014. Welding. Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded). Quality levels for imperfections.

WELD DETAIL	LOCATION	COMMENT
Butt welds in bottom flanges	At midspan	Uncommon location. Might require higher QSC level than F56. Consider increasing the section size or relocating the weld location to justify a lower QSC level.
	At part-span	Possibly subject to stress reversal. Might require higher QSC level than F56. Consider increasing the section size and justifying a lower QSC level.
	At supports	Fatigue stress range likely to be low, because of slab acting as top flange. QSC level F56 should be appropriate.
Butt welds in top flanges	Anywhere in span	Fatigue stress range likely to be low, because of slab acting as top flange. QSC level F56 should be appropriate.
Butt welds in webs	No cope hole	See comments for butt welds in bottom flanges. Shear stress range unlikely to be significant.
	At cope hole	A stress concentration factor of 2.4 may increase the range above QSC level F56. Either avoid the detail or infill the cope afterward.
Fillet weld attachment to flange	At transverse stiffener (non-bearing).	This is usually detail category 80 and may need a higher QSC level than F56 in midspan regions. Consider increasing the section size and justifying a lower QSC level.
	Bearing plate, at support.	This may be a detail category 36 detail and the flange must be designed for its category. Do not specify a lower QSC level than the recommended minimum F56.
Bearing stiffener	Weld throat	This is a detail category 36 and must be designed as such. The recommended minimum QSC level F56 should be specified.
	Weld toe on flange.	This may be a detail category 71 detail but fatigue stress range is likely to be low and QSC level F56 is likely to be appropriate.
Fillet welded, load carrying attachment (bracing etc.)	Weld throat, in shear	This is a detail category 80 and may need a higher QSC level than F56. Consider increasing weld size and justifying a lower QSC level.
	Attached plate	This may be a detail category 40 but fatigue stress in the flange plate likely to be low and QSC level F56 is likely to be appropriate.
Shear stud attachment	Stud weld	This is a detail category 90 detail but no QSC applicable as no scope to vary inspection level/criteria.
	Flange	This is a detail category 80 but no QSC applicable as no scope to vary inspection level/criteria so no need to specify other than default.

Table 1 Suggested requirements in typical composite highway bridges

WELD DETAIL	LOCATION	COMMENT
Butt welds in flanges and floor plate	All locations	All butt welds are working close to their detail category 80 fatigue stress limit and considered QSC level F90 as there is no QSC level F80.
Butt welds in webs	All locations, cope holes not permitted.	All butt welds are working close to their detail category 80 fatigue stress limit and considered QSC level F90 as there is no QSC level F80.
Cover Plate (doubler plate) welded to top flange	End of welded attachment, weld toe on flange	The detail category varies between 36 and 56 and the top flange fatigue stress is low. The default QSC level F56 applies. The cover plate has been profiled to minimise stress concentrations.
	End of welded attachment, weld throat	The detail category is 36 and the fatigue stress is kept low by profiling the cover plate low. The default QSC level F56 applies.
	Weld throat, in shear	The detail category is 80 but the fatigue stress is low and the default QSC level F56 applies.
Longitudinal fillet weld between web and top flanges	Weld throat, in shear	The detail category is 80 but the weld size has been specified to reduce the fatigue stress for the QSC level F71 to be applicable.
Longitudinal fillet weld between web and floor plate	Weld throat, in shear	The longitudinal fillet weld between the web and the floor plate is a large weld and stressed close to its fatigue stress limit. QSC level F90 is specified in the region nearest the bearings as there is no QSC level F80 and a larger weld would not be appropriate. Towards midspan, the longitudinal fatigue stresses reduce and the default QSC level F56 applies.
Fillet weld attachment to flange and floor plate	At transverse stiffener (non-bearing), weld toe on flange or floor plate	This is a detail category 80 detail but the thick floor plate and flanges plates keep the fatigue stress low and the default QSC level F56 applies.
	Weld throat, in shear	This is a detail category 80. The lower part of the stiffener section works hard in fatigue due to U-frame action and QSC level F90 is required as there is no QSC level F80.
	Floor plate rib, weld toe on flange	This is a detail category 80 detail. The thick floor plate keeps the fatigue stress low and the default QSC level F56 applies.
	Weld throat, in shear	This is a detail category 80. The effective section works hard in fatigue (U-frame action and the floor spanning between main girders). QSC level F90 is required as there is no QSC level F80.
	Bearing plate, at support	The detail is either category 36, 40 or 45. The fatigue stresses are low and the default QSC level F56 applies.
Bearing stiffener	Weld throat, in shear	This is a detail category 80. The stiffener section works hard in fatigue due to the bearing restraint but the fatigue stress is low enough to specify a QSC level F71.
	Weld toe on flange.	This is a detail category 80 detail but the fatigue stress is low and the default QSC level F56 applies.

Table 2 Requirements in a standard Network Rail U-type railway bridge (series NR/CIV/SD/1300), which specifies QSC level F56 unless specified otherwise on the draw-ings. List not exhaustive

WELD DETAIL	LOCATION	COMMENT
Fillet welded attachment: uplift bracket to flange	Attached plate	This is a detail category 71 detail but the fatigue stress is low and the default QSC level F56 applies.
U-frame spreader plate	Weld toe on web.	This is a detail category 80. The lower part of the stiffener section works hard in fatigue due to U-frame action and QSC level F90 is required as there is no QSC level F80.
Shear stud attachment	Stud weld	This is a detail category 90 detail. QSC not applicable.
	Flange	This is a detail category 90 detail. QSC not applicable.

Table 2 (cont.)