

ON THE FATIGUE BEHAVIOUR OF HOT DIP GALVANIZED STRUCTURAL STEEL DETAILS

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ABSTRACT

Today, the industrial and scientific community is devoting increasing attention to the effect of hot dip galvanizing on the fatigue strength of structural steel details. In structures such as bridges, hot dip galvanized (HDG) steel is quite often used. Along their lifetime, such structures are repeatedly submitted to stresses of varying amplitudes, leading to fatigue usually being the design criterion. In Germany, recent experimental work on a range of HDG details was carried out, which led to the publication of a guideline recognized as relatively conservative towards HDG components in steel bridge constructions. While, also quite recently, in Norway, recent studies on the behaviour of bolted HDG joints submitted to fatigue concluded that quite similar behaviour compared to uncoated steel equivalents can be expected. The present paper re-investigates, in a uniform and transparent way, the available data for similar uncoated and HDG details. In total, the data for 8 details are presented and discussed. One tries to respond to the question if hot dip galvanizing has such a detrimental effect that, the rules of current version of EN 1993-1-9 should be amended. Finally, the authors give guidance on how the current design rules concerning HDG details should be amended. These guidelines take into account the most recent draft revision of EN 1993-1-9, under preparation by the CEN/TC 250/SC 3 technical group responsible by Eurocode 3.

1 INTRODUCTION AND PROBLEM POSITIONING

The durability of structural steel components in service conditions is influenced by environmental factors as well as specific practical considerations such as the presence of pits or re-entrant angles. The use of appropriate corrosion protection systems plays a pivotal role in engineering design. Hot dip galvanizing is a recent but relatively widely used coating system in sectors such as the construction one, where hot dip galvanized (HDG) bridges are relatively often encountered in practice. In Europe, a bridge is designed and executed to a targeted service life of 100-120 years (EN 1990, 2002), thus resisting all actions and influences likely to occur during erection and lifetime with appropriate degrees of reliability. As common practice in the construction industry, the design of galvanized components in bridge construction deals with these requirements based on Eurocodes. However, there is still some scepticism on the part of the engineers' community on the use of galvanized structural steel members in bridges, due to a lack of knowledge and design recommendations regarding their fatigue behaviour (Rademacher, 2017).

Galvanized steel structures have numerous advantages in economic and environmental aspects (Sun & Packer, 2017). As a surface treatment, hot dip galvanizing protects the core material from corrosion and environmental agents. The service life of metal coatings is generally higher than for traditional paint systems. The achieved service life largely depends on the chosen metal and its thickness and is slightly influenced by the application method (Corus Construction & Industrial, 2004; Corus Construction & Industrial, 2005). Service life of metallic zinc coatings, such as hot dip galvanizing, according to the exposure categories are given in EN ISO 14713-1 (ISO 14713-1, 2009). A minimum and a maximum service life higher than 40 years is indicated when the coating thickness reaches 200µm. Furthermore, actual information is available on galvanized steel coatings for steel bridges that have been in service indeed for more than 40 years (Deacon, 2015), in which a more than sufficient measured coating thickness remains.

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50 During hot dip galvanizing, the layer of zinc is metallurgically bonded to the base metal. The
51 metallurgically bond may directly affect the crack initiation in structural steel elements withstanding
52 high level of fatigue loads as well as a large number of load cycles, thus affecting their fatigue
53 behaviour. Therefore, several authors have tried to correlate the fatigue behaviour of steel
54 components to the galvanizing coating effect over the years (Nasr, et al., 2017; Bergengren &
55 Melander, 1992; Aden-Ali, et al., 2009; Vogt, et al., 2008; Nilsson, et al., 1989; Buršák & Mamuzić,
56 2007; Camurri P., et al., 2005; Sun & Packer, 2017), reporting a prevailing reduction on the fatigue
57 strength of galvanized thin plates of steel. It should be noted, however, that these studies deal with
58 unnotched specimens without stress concentration effects or geometrical discontinuity, mainly aimed
59 at applications such as steel wires for bridges and automotive industries.

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61 The aim of the present paper is to review this recent data, as well as its significance to the design of
62 galvanized steel bridges. The authors try to finally respond to the question if hot dip galvanizing has
63 such a detrimental effect that, ultimately, the rules of the current version of EN 1993-1-9 (EN 1993-1-
64 9, 2005) should be amended. More importantly, the authors give guidance on how the current design
65 rules should be amended in the eventuality of substantial differences between the resistances of
66 HDG and uncoated details under fatigue. These guidelines take into account the most recent draft
67 revision of EN 1993-1-9 (prEN 1993-1-9, 2020), under preparation by the CEN/TC 250/SC 3 group
68 responsible by Eurocode 3. The paper is structured in the following way: in Section 2 the typical stress
69 life method is briefly described, in Section 3 the fatigue data on galvanized steel details is
70 recapitulated and, in Section 4, it is re-analysed and compared to reference data on similar carbon
71 steel details, collated in the literature, for the same detail category. Finally, conclusions are drawn,
72 and recommendations are proposed.

2 STRESS-LIFE APPROACH

The Stress-Life (S-N) approach to fatigue assessment was introduced by Wöhler in the 1860s (Suresh, 1998). The first S-N curves were developed to understand railcar axle failures, comparing nominal stress amplitudes in the critical cross-section to the endurable nominal stress amplitudes. This approach was later transferred to other industries. In structural engineering design, it is common practice to evaluate fatigue strength and service life (up to final fracture) based on the so-called nominal stress approach. Nominal stress ranges in critical cross-sections are thus compared against the S-N curves (or Wöhler curves) given in EN 1993-1-9 (EN 1993-1-9, 2005). These assessment are summarized in Table 1 and should be applied for all grades of structural steels, stainless steels, and unprotected weathering steels except where noted otherwise in the detail category tables. Materials must also conform to the toughness requirements treated separately in EN 1993-1-10 (EN 1993-1-10, 2005) to avoid brittle fracture and the rules are not applicable for nominal stress ranges higher than $1.50 f_y$, where f_y is the yield strength. Therefore, in the past, designers have reasonably assumed that the method did apply to galvanized steel, based on the available information.

Table 1 – Typical fatigue assessment procedure

Typical fatigue assessment procedure	Description
1. Identification of structural locations ("details")	Structural discontinuities, joints, etc.
2. Definition of stress range $\Delta\sigma$	Based on maximum and minimum loads as well as number of cycles.
3. Identification of correction factors	Application of stress concentration and thickness correction factors to the stress range.
4. Identification of fatigue strength curve for each detail	S-N curves are typically dependent the considered detail category $\Delta\sigma_c$ and fabrication methods.
5. Fatigue analyses	Calculation of the damage equivalent stress range.
6. Further actions in order to improve the fatigue life	Improve fatigue assessment using: <ul style="list-style-type: none">- more refined stress assessment,- hot spot stress method,- fracture mechanics, Improve calculated fatigue capacity by: <ul style="list-style-type: none">- changing detail geometry (design stage),- post-weld treatment (construction stage),

In principle, there should be one fatigue strength curve per considered constructional detail, leading to a code which would be unusable in practice. Therefore, structural details are classified in categories, with a corresponding S-N curve. These curves have a fixed slope (m) and are characterized by the reference value of the detail category fatigue strength ($\Delta\sigma_c$) at 2×10^6 cycles, as described in Figure 1. When a construction detail is subjected to a larger number of cycles, the constant amplitude fatigue limited (CAFL) may be reached. CAFL is the limiting value for constant spectra of stress ranges that a detail is expected to withstand an infinite number of stress cycles without fatigue damage EN 1993-1-9 (EN 1993-1-9, 2005). Generally, S-N curves are derived from fatigue tests performed on laboratory specimens, which typically reproduce the detail to be studied, and therefore include:

- (i) steel with different mechanical behaviour (including high-strength steel),
- (ii) the stress concentration due to the particular geometry,
- (iii) the stress direction,
- (iv) the expected crack location,
- (v) the residual stresses,
- (vi) the influence of the welding and
- (vii) post-welding procedures if any.

Quite a lot of research focused on S-N curves, however, no internationally recognized procedure for fatigue testing and design of experiments has been established. In that respect, the fatigue test data found in the literature often show inconsistencies. This issue is analysed in detail in Chapter 4.

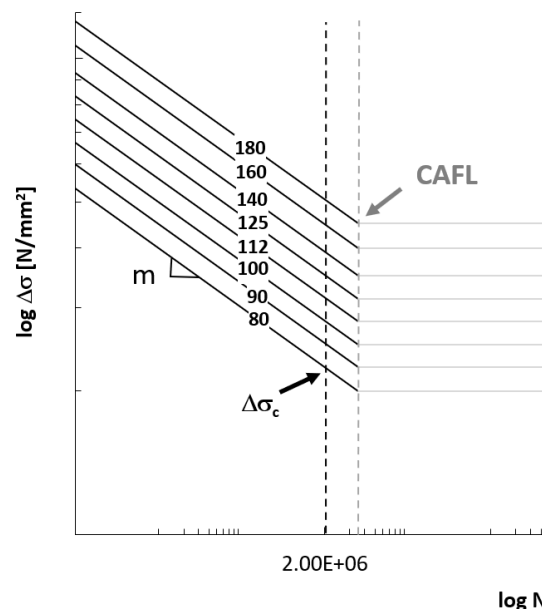


Figure 1 – Reference values of the fatigue strength curves.

The popularity of the nominal stress approach comes from its simplicity. Nonetheless, the following drawbacks are to be considered: (i) it is not applicable when the studied detail geometry is so complex that it is difficult to assign a detail category to it; and (ii) it is unable (or impractical) to represent complex loading conditions. More advanced methodologies, such as the hot spot stress method and fracture mechanics (Hobbacher, 2016), may be applied in order to improve fatigue life estimations.

3 FATIGUE DATA ON HDG FATIGUE DETAILS

Concerning HDG fatigue details, it is worth recapitulating the most recent scientific contributions found in the literature. A summary of these contribution can be found in Table 2, as well as the fatigue studies whose authors have addressed concerns, suggesting lower fatigue detail categories.

Table 2 – Fatigue tests on HDG steel details.

Fatigue detail		EN 1993-1-9 (EN 1993-1-9, 2005)		Classification according to the authors				
		$\Delta\sigma_c$ [MPa]	m	Ref.	$\Delta\sigma_c$ [MPa]	m	R	Ps [%]
Plates and rolled sections	Rolled or extruded plates with as rolled edges*	160	3.00	(Ungermann, et al., 2014)	140	3.00	0.05	97.70
	Gas cut or sheared plates with subsequent grinding	140	3.00	(Rademacher, 2017)	140	3.00	0.10	97.70
	Gas cut or sheared plates with subsequent deburring*	125	3.00	(Ungermann, et al., 2014)	112	3.00	0.05	97.70
Bolted connections	Plate weakened by a drilled central hole*	90	3.00	(Valtinat & Huhn, 2003)	80	5.90	0.10	95.00
				(Berto, et al., 2015)	87	3.74	0.00	97.70
	Bolted connection with drilled holes and preloaded bolts*	112	3.00	(Valtinat & Huhn, 2003)	112	>5.90	0.10	97.70
				(Berto, et al., 2016)	100	3.75	0.00	95.00
	Bolted connection with punched holes and preloaded bolts	112	3.00	(Valtinat & Huhn, 2003)	112	>5.90	0.10	95.00

	Bolts and rods with rolled or cut metric screw threads in tension	56	3.00	(Weber, 2010)	56	3.00	0.00	97.70
Fillet welds (FW)	Cruciform FW*	80	3.00	(Ungermann, et al., 2014)	80	3.00	0.05	97.70
				(Berto & Fergani, 2017)	83	2.94	0.00	90.00
	Manual welding – longitudinal FW	100	3.00	(Rademacher, 2017)	100	3.00	0.10	97.70
	Manual welding - longitudinal FW over transverse butt weld	80	3.00	(Rademacher, 2017)	80	3.00	0.10	97.70
	Vertical stiffeners welded to a rolled section or plate girder	80	3.00	(Rademacher, 2017)	80	3.00	0.10	97.70
Butt welds (BW)	Transverse BW in rolled section*	90	3.00	(Rademacher, 2017)	80	3.00	0.10	97.70
	Flush-ground BW in plates*	112	3.00	(Ungermann, et al., 2014)	100	3.00	0.10	97.70
	Transverse BW in plates with height of weld convexity < 20% of weld width	80	3.00	(Rademacher, 2017)	80	3.00	0.10	97.70
Stud shear connectors for composite application*		90	8.00	(Rademacher, 2017)	80	8.00	0.00	97.70

* Details re-analysed in the following section

The first publication related to fatigue performance of HDG notched details dates to the year 2000. Valtinat and Huhn presented a study on the fatigue behaviour of shear loaded connections in galvanized structural members, with punched holes, at the Intergalva conference (Valtinat & Huhn, 2000). This contribution was followed by another presentation at the Connections in Steel Structures conference in 2004 (Valtinat & Huhn, 2004). The tested specimens consisted of S235JR steel grade, in accordance with EN 10025-1 (EN 10025-1, 2004), with thicknesses ranging from 8.00 to 10.00 mm. The specimens were loaded in tension, with a stress ratio R between lower and upper load of 0.1. Two different fatigue details were evaluated in this study: (i) plate weakened by a central hole, (ii) bolted connection with preloaded bolts and with normal bolts. The authors observed a negative influence of combining hot dip galvanizing with the punching process for both fatigue details, as all the experimental results were lying under the S-N curve for a detail category of 112. However, it

should be noted that, in accordance to the current EN1993 1-9 (EN 1993-1-9, 2005), only double covered symmetrical fastened joints with preloaded high strength bolts fall within the fatigue category 112. Therefore, a re-analysis of this experimental data should be conducted in order to evaluate whether the data fits a fatigue strength of category 90 instead of 112. In addition, it was observed a positive effect of preloading in bolted bearing joints: when applying a preload of 50 %, the fatigue life significantly increased. It was also noted that the overall trend of the test results shows that the slope should be higher than $m=3.00$: when changing the slope from $m=3.00$ to $m=5.00$, a better agreement with the whole S-N curve for the fatigue category 112 is found, for both uncoated and HDG steel. As suggested in (Valtinat & Huhn, 2004), the use of preloaded high strength bolts with two washers can neutralize the unbeneficial influence of punching and hot dip galvanizing in the fatigue behaviour of plates weakened by a central hole, in which case the detail category 112 can safely be used.

In 2014, the results of the extensive research project FOSTA P 835 (Ungermann, et al., 2014) involving TU Dortmund, the *Staatliche Materialprüfungsanstalt Darmstadt* (MPA) of the TU Darmstadt and the *Institut für Korrosionsschutz Dresden GmbH*, were reported in (Ungermann, et al., 2014). This research project was followed by publications (Ungermann, et al., 2014), guidelines (Ungermann, et al., 2016) and a PhD thesis (Rademacher, 2017). The aim of the project was to establish scientific basis for the use of hot dip galvanizing as corrosion protection for steel and composite bridges of short and medium spans. With this aim, a database of typical fatigue details was elaborated. This database was cordially shared with the authors of this paper. Within this database, fatigue tests on ten distinct HDG details can be found: i) rolled or water-jet cut and subsequently milled plate with as rolled edges (detail category 160); ii) gas cut plate with subsequent grinding (detail category 140); iii) gas or water-jet cut plate with subsequent deburring (detail category 125); iv) longitudinal fillet weld (detail category 100); v) longitudinal fillet weld over transverse butt weld (detail category 80); vi) vertical stiffener welded to a rolled section or plate girder (detail category 80); vii) transverse butt

157 weld in rolled section (detail category 90); viii) flush-ground butt weld in plates (detail category 112);
158 ix) transverse butt weld in plates with height of weld convexity $< 20\%$ of the weld width (detail
159 category 80); and x) stud shear connector for composite application (detail category 90). Concerning
160 the first fatigue detail, i. e., rolled or water-jet cut and subsequently milled plates with as rolled edges
161 (detail category 160), fatigue tests were performed on HDG specimens consisting of S355 J2+N
162 structural steel plates with thicknesses equal to 10mm; a stress ratio $R=0.05$ was employed in this set
163 of tests. The authors concluded that the detail category should be reduced to 140. Concerning the
164 second detail category, i. e., fatigue tests were performed on HDG specimens consisting of S460M
165 structural steel structural steel plates with thicknesses equal to 14.30 mm; a stress ratio $R=0.10$ was
166 employed in this set of tests. The authors found no reduction on fatigue strength for HDG details.
167 Concerning the third fatigue detail, i. e., gas or water-jet cut plates/sections with subsequent
168 deburring (detail category 125), fatigue tests were performed on HDG specimens consisting of
169 different thicknesses and structural steel grades: S355J2+N with thickness equal to 10mm, S355JR+AR
170 with thickness equal to 17.50mm, P460NL2/NH with thickness equal to 10 mm, and S700 MC with
171 thickness equal to 15 mm. The authors concluded that the detail category should be reduced to 112,
172 as the resulting S-N curve reached only 117 MPa at 2×10^6 cycles. Regarding the fourth and fifth
173 fatigue detail, i. e., longitudinal fillet weld (detail category 100) and longitudinal fillet weld over
174 transverse butt weld (detail category 80), four-point bending tests were performed on three HDG
175 welded I beams (313.60x150.00x31.80x22.23 and 294.46x130x22.23x17.50). Furthermore, small
176 scale specimens were used to simulate the full-scale tests, to increase the number of tests. The used
177 structural grade was S460M and the stress ratio $R=0.10$. The authors found no significant reduction
178 on fatigue strength for HDG details. Regarding the sixth fatigue detail, i. e., vertical stiffener welded to
179 a rolled section or plate girder (detail category 80), four-point bending tests were performed on HDG
180 IPE270 profiles with vertical stiffeners welded at the supports and at the midpoint of the beam. The
181 used structural grade was S355J2+M and the stress ratio $R=0.10$. The authors stated that the HDG
182 detail could also be sorted into detail category 80, although in other small-scale tests a reduction of

fatigue strength was found. Regarding the seventh fatigue detail, i. e., transverse butt weld in rolled section (detail category 90), four-point bending tests were performed on HDG HE400B profiles. The used structural grade was S355J2+M and the stress ratio $R=0.10$. The authors concluded that the detail category should be reduced to 80, however, the resulting S-N curve only reached 74MPa at 2×10^6 cycles, since all results were above the S-N curve for detail category 80. Regarding the eighth fatigue detail, i. e., flush-ground butt weld in plates (detail category 112), the authors concluded that the detail category should be reduced to 100, as the resulting S-N curve only reached 98 MPa at 2×10^6 cycles. Regarding the ninth fatigue detail, i. e., transverse butt weld in plates with height of weld convexity $< 20\%$ of the weld width (detail category 80), the authors confirmed detail category 80 for this detail, although they found a reduction on the fatigue strength for HDG details. Regarding the tenth fatigue detail, i. e., stud shear connector for composite application (detail category 90), the authors concluded that the detail category should be reduced to 80, as the resulting S-N curve only reached 80 MPa at 2×10^6 cycles. In additionally to the fatigue tests performed under this research project, reference is made in (Rademacher, 2017) to fatigue tests on bolts and rods with rolled or cut metric screw threads in tension. The tests were performed within the domain of a master thesis (Weber, 2010) and no reduction on fatigue strength for HDG details was found.

In 2015, Berto et al. published a study regarding the notch effect on the fatigue behaviour of a HDG structural steel (Berto, et al., 2015). The tested specimens consisted of S355 structural steel plates weakened by a central hole, with thickness of 10mm. The holes were produced using the drilling process. Two different stress ratios, $R=0.00$ and $R=-1.00$ have been employed in this experimental study. According to the authors, the negative influence of HDG is about 25% in terms of fatigue strength, with no significant influence of the stress ratio. Nevertheless, it is concluded in the study that galvanized specimens have comparable fatigue strength to the codified fatigue strength 90. However, it should be noted that the real behaviour of the tests shows, once again, that the natural slope is smaller than $m=3.00$, with the authors using the best fitting slope for each test series.

In 2017, Berto et al. again presented a study on the fatigue behaviour of HDG bolted steel connections at the XXIV Italian Group of Fracture Conference (Berto, et al., 2017). This study follows a technical note published at the International Journal of Fatigue in 2016 (Berto, et al., 2016). The tested specimens consisted of preloaded bolted connections, with drilled holes. The plates were made of S355 structural steel, with thickness of 10mm. According to the authors, the reduction in the fatigue life of HDG bolted steel is very limited compared to uncoated joints. However, it should be noticed that the fatigue data did not fit a detail category of 112, but, after re-evaluation, of 101. Furthermore, the adopted slope was closer to $m=3.00$, as suggested by EN1993 1-9 (EN 1993-1-9, 2005), in contrast to Valtinat and Huhn (Valtinat & Huhn, 2004).

At the XXIV Italian Group of Fracture Conference, Berto et al. presented a second study on the fatigue behaviour of HDG welded steel (Berto, et al., 2017). This study was followed by paper published at the International Journal of Fatigue in 2017 (Berto & Fergani, 2017). Within these studies, fatigue tests were conducted on transverse non-load carrying fillet welded joints. The tested specimens consisted of S355J2+N structural steel, with thickness of 10mm. All specimens were tested under uniaxial tension with a stress ratio $R=0.00$. According to the authors, the HDG specimens had a lower fatigue strength. However, their strength is in the range admitted by EN1993 1-9 (EN 1993-1-9, 2005) for uncoated specimens (from 71 to 80 MPa). This conclusion was reached also considering a Strain Energy Density (SED) approach. It should be noticed, nevertheless, that the tested specimens fall within detail category 80, according to EN1993 1-9 (EN 1993-1-9, 2005) and not 71.

In all these contributions, authors tend to notice a difference in the S-N curves and often propose value greater than 3.00 for the slope of the curve. It is important to note at this stage that some studies are contradictory, sometimes proposing a lower detail category, sometimes concluding that the current categories are still appropriate for the same detail. It is the reason why all the available raw fatigue data was re-analysed in the following section. The analysis is done per detail, combining

all available studies on HDG details and comparing against fatigue tests results on uncoated specimens found in the literature.

4 RE-ASSESSMENT OF DETAIL CATEGORIES FOR HDG DETAILS

When S-N curves for constructional details are determined by testing, the reference value of the fatigue strength, $\Delta\sigma_c$, should be determined in accordance to EN1993-1-9 (EN 1993-1-9, 2005) for “a 75% confidence level of 95% probability of survival for log N”, where N is the endurance in cycles. Instructions for this statistical evaluation are given in the annex D of EN 1990 (EN 1990, 2002). Generally, the fatigue data are plotted on logarithmic scale and the statistical evaluation considers the standard deviation, the sample size and residual stress effects. Nonetheless, $\Delta\sigma_c$ may be determined according to other European codes (NORSOK, 2013; DNV-GL, 2014), which do not consider, for example, the influence of a small sample size through confidence levels. These codes refer to mean minus two standard deviations, corresponding to a survival probability of 97.7%. This approach was employed in the background documents for EN 1993-1-9 (prEN 1993-1-9, 2003; Brozzetti, et al., 1989). Therefore, the fatigue test data found in the literature are usually inconsistent.

In this section, the available fatigue data for similar uncoated and HDG details are re-assessed in a systematic way. These details are summarized in Table 3, as well as the respective classifications according to the current EN1993-1-9 (EN 1993-1-9, 2005) and the most recent draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020).

Table 3 – Reanalysed detail categories for HDG steel details.

Fatigue detail		EN 1993-1-9 (EN 1993-1-9, 2005)		prEN 1993-1-9 (prEN 1993-1-9, 2020)		Proposal for HDG steel details	
		Detail category	m	Detail category	m	Detail category	m
Plates	Rolled or extruded plates with as rolled edges	160	3.00	180	5.00	180	5.00
	Gas cut or sheared plates with subsequent deburring	125	3.00	125	5.00	125	5.00
Connections	Plate weakened by a drilled central hole	90	3.00	80	5.00	80	5.00
	Bolted connection with preloaded bolts	112	3.00	112	5.00	112*	5.00*
Fillet welds (FW)	Cruciform FW	80	3.00	80	3.00	80*	3.00*
Butt welds (BW)	Transverse BW in rolled section	90	3.00	90	3.00	80	3.00
	Flush-ground BW in plates	112	3.00	112	3.00	100	3.00
Stud shear connectors for composite application		90	8.00	90	8.00	90	8.00

* More data is needed.

The statistical evaluation of the fatigue data was performed based on a lower bound limit approach for three different groups: (i) HDG steel, (ii) uncoated steel, and (iii) combined statistic population (HDG steel and uncoated steel). The S-N data is presented in graphs showing log N (endurance in cycles) as the abscissa and log $\Delta\sigma$ (stress range) as the ordinate. For the statistical evaluation, only test data comprised between 1×10^4 and 5×10^6 with load cycles to failure are considered, in accordance with the first draft of the background document prEN 1993-1-9 (prEN 1993-1-9, 2003). Taking into account the annex D of EN 1990 (EN 1990, 2002), the evaluation proceeds in four steps: (i) a linear regression analysis with fixed slope $m=3.00$; (ii) an evaluation of $\Delta\sigma_c$ at 2×10^6 with $m=3.00$; (iii) a linear regression analysis with fixed slope $m=5.00$; (iv) an evaluation $\Delta\sigma_c$ at 2×10^6 with $m=5.00$. In this evaluation, a Gaussian log-normal distribution is assumed and the $\Delta\sigma_c$ values represent 95% survival probability calculated from the mean, based on a two-sided confidence of 75%.. This method is equal to about mean minus two standard deviations at about 20 specimens (Hobbacher, 2016).

However, this approach results in more conservative values of $\Delta\sigma_c$, when evaluating smaller statistic populations, which is the case of many HDG steel populations found in literature. The authors propose therefore a combined statistic population (HDG steel and uncoated steel). The data for the 8 details selected in section 4 are in this section, in this manner, presented and discussed.

Finally, it should be noted that residual stresses effects were not considered in the re-assessment of detail categories. In order to properly consider the greater effects of residual stresses in real sized structures, high R values ($R=0.50$) should be employed during fatigue testing (Krebs & Kassner, 2007). Nevertheless, the notch effect on constructional details reduces the mean stress dependence. An alternative approach would be to systematically perform tests with $R=0.00$, with a posterior reduction of $\Delta\sigma_c$ (Hobbacher, 2016). As summarized in Table 2

Table 2, low and inconsistent R values were used in fatigue tests on HDG steel details. Concerning fatigue tests on uncoated steel, R values follow generally the same tendency, being many times omitted. Residual stresses effects were therefore neglected in the current analysis.

4.1 Rolled or extruded plates with as rolled edges

The fatigue data for rolled or extruded plates with as rolled edges published in the FOSTA P 835 report (Ungermann, et al., 2014) is presented in Figure 2, together with the S-N curves for this detail. In Figure 2 to Figure 10, S-N curves are provided for three different statistical populations: HDG tests, uncoated steel tests and the combined statistical population. The codified detail categories are also provided. Presently, the collected statistical population from the literature (both for uncoated and HDG specimens) does not fit the detail category 160, proposed in EN 1993-1-9 (EN 1993-1-9, 2005) for carbon steel. It is important to note that the S-N curve derived from the fatigue data given in the background document (prEN 1993-1-9, 2003) for the EN 1993-1-9 also lead to a detail category lower than 160. However, inaccuracies might be present in these results, as the fatigue data is often derived from relatively old tests, to which digital data is not available. Nevertheless, one would have to

decrease it to 140 to have consistency between a S-N curve with $m=3.00$ and the whole set of data, as proposed in the literature (Rademacher, 2017). Furthermore, the cloud of points is clearly valid for a fatigue life ranging from 1×10^5 up to about 2×10^6 cycles. In this region, the HDG data seems to roughly fit the uncoated data. However, it is extremely difficult to conclude for a lower amount of cycles since there is not much data available for uncoated specimens.

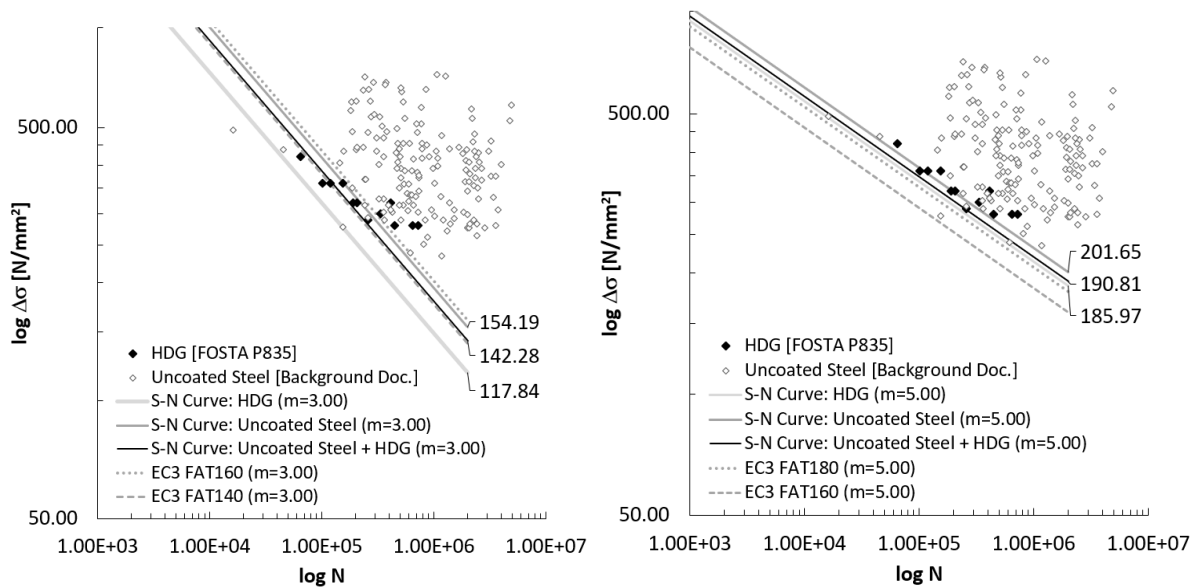


Figure 2- Statistical evaluation: Rolled or extruded plate with as rolled edges.

Taking Figure 2 into consideration, it is however quite clear that the statistical populations would better be represented using a value for $m=5.00$, as almost all the data point would lay above S-N curve representing the combined statistical population. This goes in accordance with the most recent draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020), which suggests for this detail the category 180 with a fixed slope $m=5.00$. Furthermore, when using $m=5.00$, one should notice the decreased deviation between the S-N curves representing the different statistical populations (HDG steel, uncoated steel and combined statistical population). Given the current state of the art, the new detail category proposed in the draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020) satisfies all the statistical populations and no differentiation should be made.

4.2 Gas cut or sheared plates with subsequent deburring

The fatigue data for HDG gas cut or sheared plates with subsequent deburring is presented in Figure 3. As previously mentioned, tests were performed in different steel plates: S355 J2+N with thickness equal to 10 mm, S355JR+AR with thickness equal to 17.50 mm, P460NL2/NH with thickness equal to 10 mm, and S700 MC with thickness equal to 15 mm (see (Ungermann, et al., 2014) and (Rademacher, 2017)). The fatigue data available in the background document (Brozzetti, et al., 1989) for the EN 1993-1-9 is also presented. The detail category according to EN 1993-1-9 (EN 1993-1-9, 2005) is 125, while the resulting S-N curve representing the combined statistic populations reached 116.00 MPa at 2×10^6 cycles. Although in essence 116 is not extremely far from 125, one can clearly see that there is a drop from uncoated to HDG data. Furthermore, when comparing the HDG data of tests to the tests performed in the frame of the establishment of the code, the CAFL seems to have already been reached at 1×10^6 cycles, as in the data of background document. It is worth pointing that for bridge applications, the domain of interest is beyond 2×10^6 cycles.

As noticed in the previously evaluated detail, the statistical populations would better be represented using a higher value for m . This goes in accordance with the most recent draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020), which suggests for this detail the category 125 with a slope $m=5.00$. Given the current state of the art, the new detail category proposed in the draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020) satisfies all the statistical populations and no differentiation should be made. However, a higher detail category should be used to classify this fatigue detail, i. e., detail category 140 and a slope $m=5.00$. When looking into Figure 3, one may notice that all the stress ranges $\Delta\sigma_c$ at 2×10^6 are much higher than 125 with $m=5.00$.

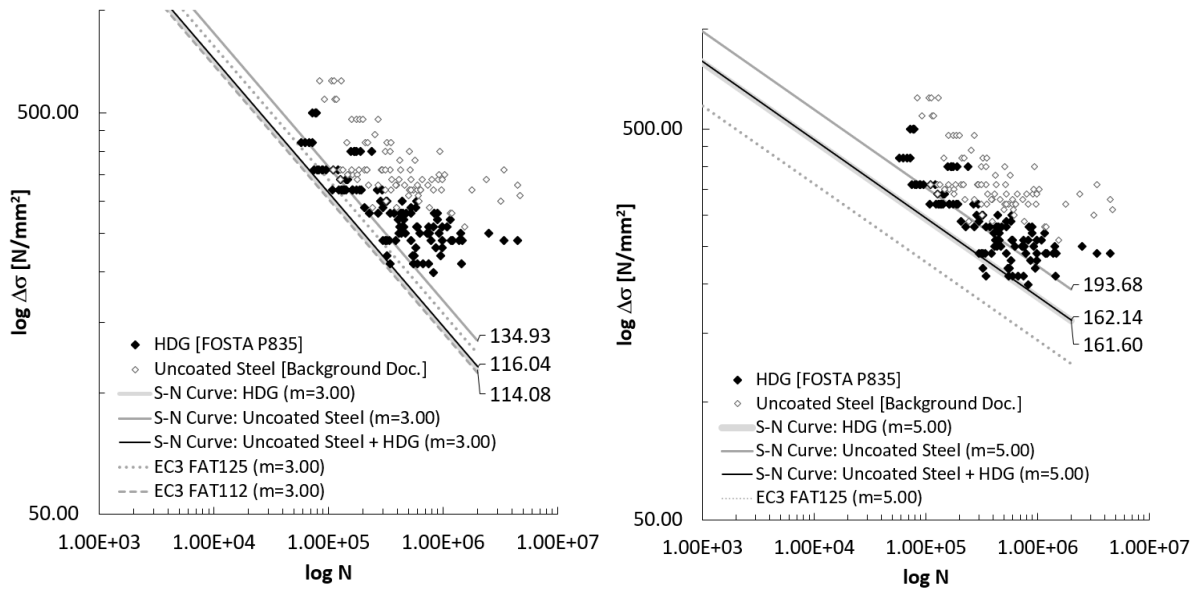


Figure 3- Statistical evaluation: gas cut or sheared plates with subsequent deburring.

4.3 Plate weakened by a drilled central hole

It is of common knowledge that the manufacture of a plate (i.e., as rolled edges, gas cut, grinding) and its respective hole (i.e., drilled, punched, gas cut) have an influence on the fatigue strength of the specimens. This fatigue detail has category 90 with a fixed slope $m=3.00$, according to the current version of the EN 1993-1-9 (EN 1993-1-9, 2005). Considering the available fatigue data for uncoated and HDG specimens, a fatigue category of 80 (i.e. lowered by one category), with fixed slope $m=3.00$, may be used (see Figure 7). Nevertheless, the recent draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020) suggests a new detail category for this detail, i.e., detail category 80 with a slope $m=5.00$. Given the current state of the art, the new detail category proposed in the draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020) satisfies all the statistical populations and no differentiation should be made. However, a higher detail category may be used to classify this fatigue detail, i. e., detail category 90 and a slope $m=5.00$.

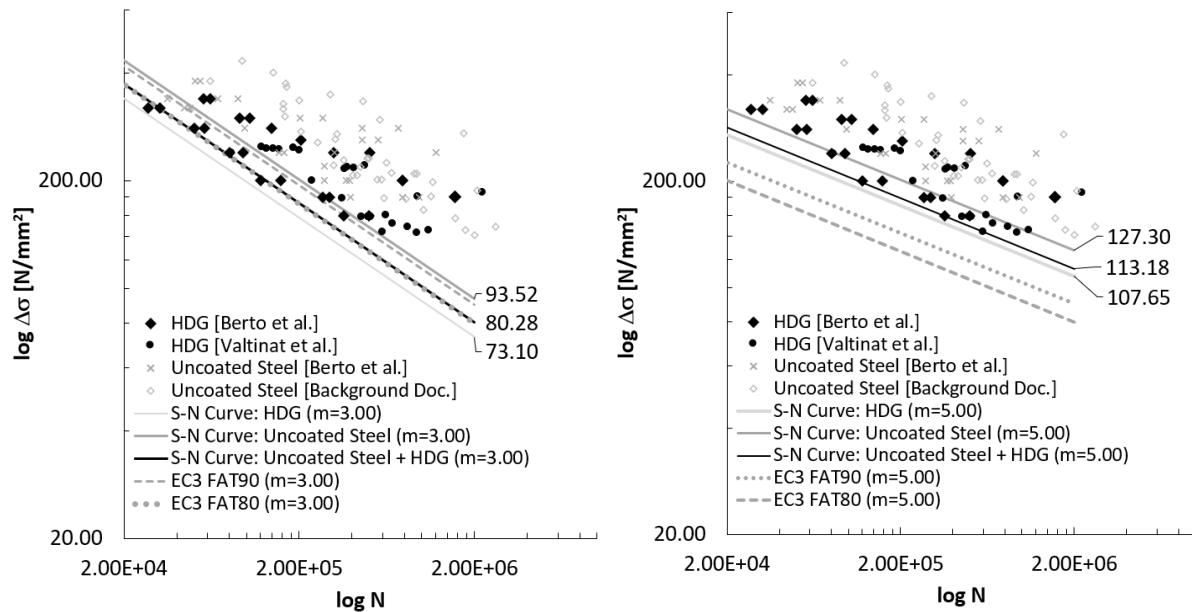


Figure 4- Statistical evaluation: plate weakened by a drilled central hole.

4.4 Bolted connections with preloaded bolts

The fatigue data for bolted connections with preloaded bolts published by Valtinat and Huhn (Valtinat & Huhn, 2003) and Berto et al. (Berto, et al., 2016) is presented in Figure 5. This fatigue detail has category 112 with a fixed slope $m=3.00$, according to the current version of the EN 1993-1-9 (EN 1993-1-9, 2005). However, it should be noticed that a totally different slope is portrayed in both test series. While the data by Valtinat and Huhn (Valtinat & Huhn, 2003) follows a slope m higher than 5, the data by Berto et al. (Berto, et al., 2016) is better portrayed by a slope m closer to 3. This fact is noted by Berto et al. (Berto, et al., 2016). Consequently, it is not possible to consider a statistic analysis of the combined statistic population, as the resulting S-N curve is too conservative due to the huge deviation on the fatigue test results.

Here again, the most recent draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020) a new category for this detail, i.e., detail category 112 with a slope $m=5.00$. Nonetheless, when analysing separately the data by Valtinat and Huhn (Valtinat & Huhn, 2003) and Berto et al. (Berto, et al., 2016), both stress ranges $\Delta\sigma_c$ are higher than 112 at 2×10^6 (134.28 and 119.65 respectively). Given the current state of

the art, the new detail category proposed in the draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020) satisfies all the statistical populations and no differentiation should be made. However, more fatigue tests are desirable to support keeping the new detail category.

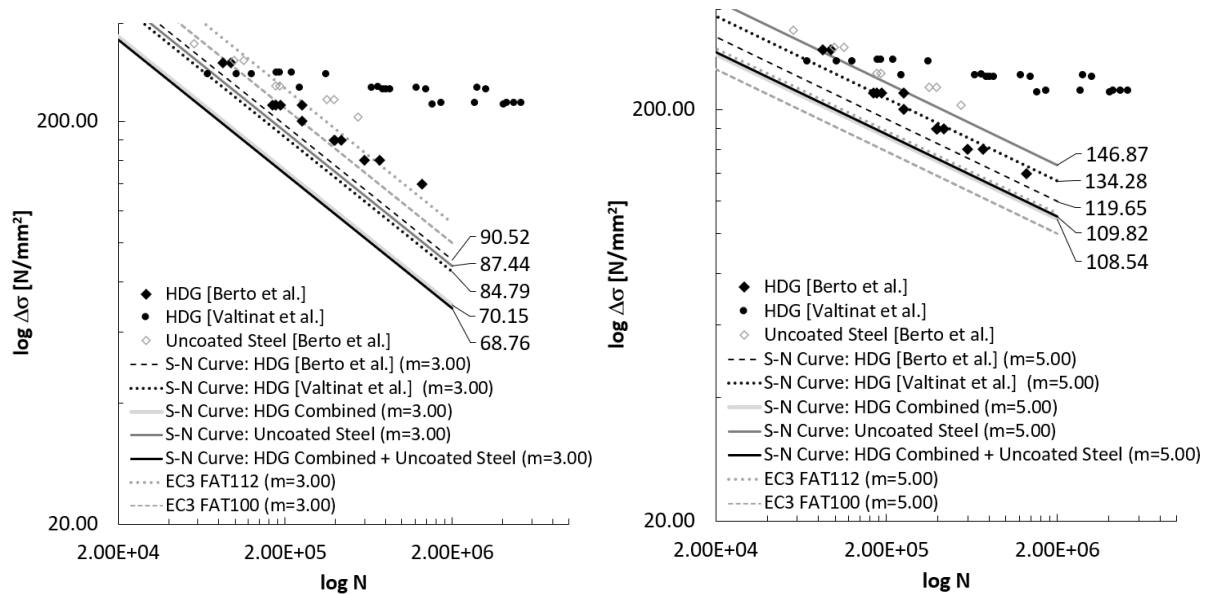


Figure 5- Statistical evaluation: bolted connection with preloaded bolts.

4.5 Fillet welded cruciform specimens

The fatigue data for fillet welded cruciform specimens published in the FOSTA P 835 report (Ungermann, et al., 2014) and Berto et al. (Berto & Fergani, 2017) is presented in Figure 6. This fatigue detail has category 80 with a fixed slope $m=3.0$, according to the current version of the EN 1993-1-9 (EN 1993-1-9, 2005) and the recent draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020). The trend of the data suggests a much lower detail category, as the stress ranges $\Delta\sigma_c$ calculated at 2×10^6 is 65.96 for the combined HDG statistical population. Here again, the resulting S-N curve is too conservative due to the huge deviation on the fatigue test results presented by the different authors. While the results by FOSTA P 835 project (Ungermann, et al., 2014) fit the class category 80 by a large margin, there results presented by (Berto & Fergani, 2017) raise doubts, as the detail should be classified with class 75 instead of 80. However, when taking all data into account (HDG and uncoated steel), a category of 77.63 is found. As these details play a very important role in the design of girder

bridges, being many times the design driving criteria of girder bridges at the midspan sections, tests are desirable to clarify the matter. Furthermore, two specimens failed below the S-N curve for the detail category 80.

To simplify the EN 1993-1-9 (EN 1993-1-9, 2005) approach, the authors are not in favour of changing the rules for HDG details. One would want to have more test results to justify amending the code for HDG specimens. Here again, at 2×10^6 cycle, one seems to have already reached the CAFL and more tests beyond this stress range would be of high interest.

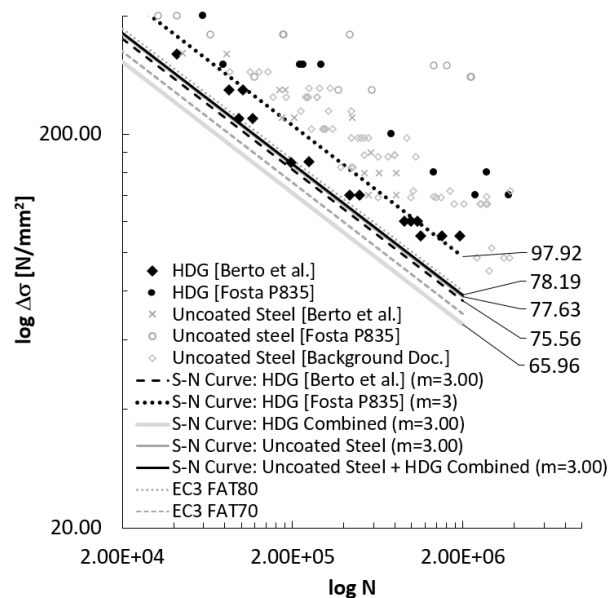


Figure 6- Statistical evaluation: fillet welded cruciform.

4.6 Flush-ground butt-welded plate specimens

The fatigue data for flush-ground butt-welded plate specimens published in the FOSTA P 835 report (Ungermann, et al., 2014) is presented in Figure 7. This fatigue detail has category 112 with a fixed slope $m=3.00$, according to the current version of the EN 1993-1-9 (EN 1993-1-9, 2005) and the recent draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020). Presently, the collected statistical population from the literature (both for uncoated and HDG specimens) does not fit the proposed detail category 112 of EN 1993-1-9 (prEN 1993-1-9, 2020). However, inaccuracies may be present in

the test results for uncoated steel from (Maddox, 1997) as the study dates to 1997. Nevertheless, one would have to decrease it to 100 to have consistency between a curve with a slope $m=3.00$ and the whole set of data (see Figure 7). Here again, and especially for the data from (Maddox, 1997), a higher value of m seems more adequate. Furthermore, one would expect the slope of this detail to be modified to $m=5.00$ in the revision of EN 1993-1-9 (prEN 1993-1-9, 2020), similarly to plain steel members, as the geometrical imperfections are removed this detail. When keeping the slope $m=3.00$, a note should be added to the EN 1993-1-9 (prEN 1993-1-9, 2020), suggesting the use the next lower detail category for flush-ground butt-welded plate specimens made of galvanised steel, i. e., detail category 100 with $m=3.00$.

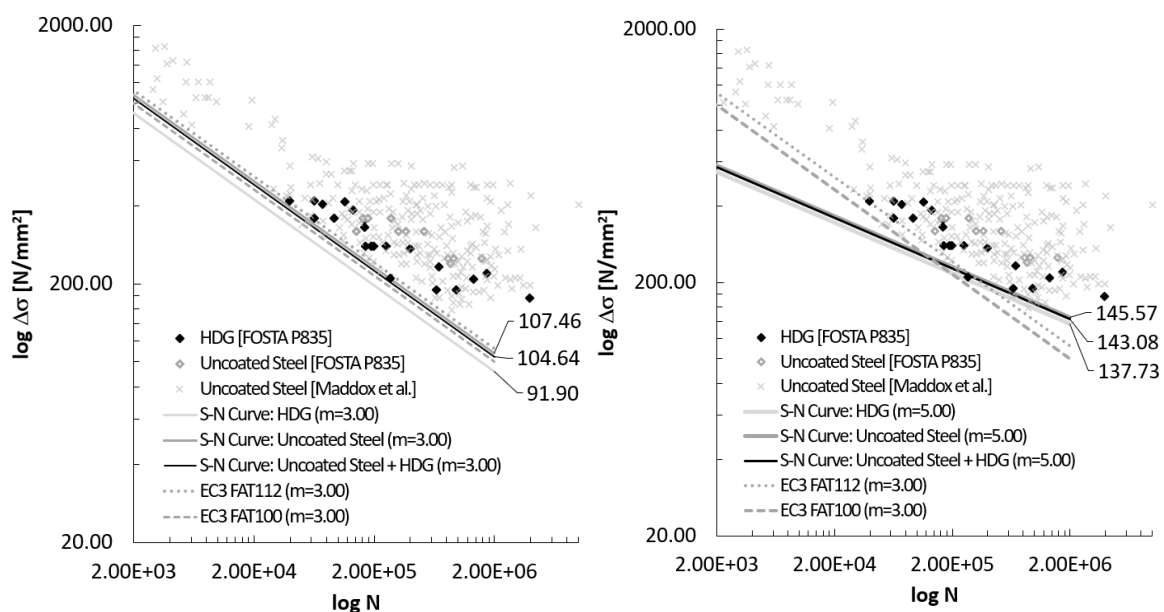


Figure 7- Statistical evaluation: flush-ground butt-welded plate specimen.

4.7 Transverse butt weld in rolled section

In Figure 8, the fatigue data by Rademacher (Rademacher, 2017) was complemented with test results on uncoated steel from the background document (prEN 1993-1-9, 2003), as well as another study, published by Munse and Stallmeyer (Munse & Stallmeyer, 1957). This fatigue detail has category 90 with a fixed slope $m=3.00$, according to the current version of the EN 1993-1-9 (EN 1993-1-9, 2005)

and the recent draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020). For HDG steel details, the S-N reached only 69.73 MPa at 2×10^6 cycles.

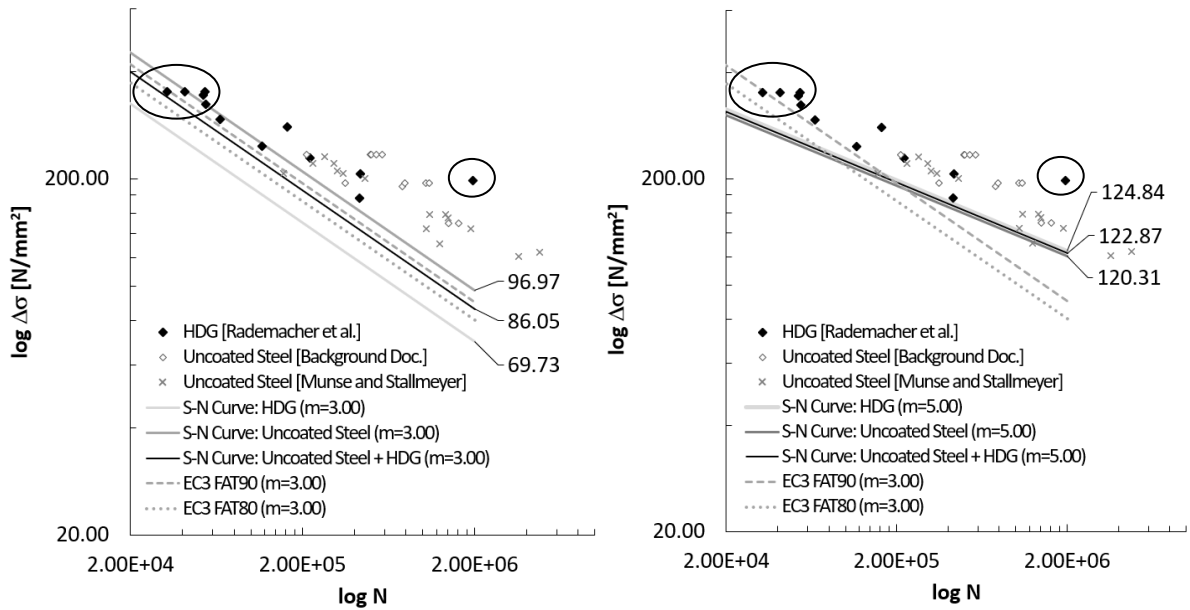


Figure 8- Statistical evaluation: transverse butt weld in rolled section.

However, this S-N curve was derived from an unscreened statistical population. When excluding the fatigue tests performed with stress ranges equal or higher than the yield strength of the base material (S355), or fatigue tests withstanding much more cycles than expected, the S-N reached significantly higher values as shown in Figure 9. Here again, a higher value of m seems more adequate. When using $m=5.00$, the detail category may be maintained, with or without screening (Figure 8 and Figure 9). Alternatively, a note should be added to the EN 1993-1-9 (prEN 1993-1-9, 2020), suggesting the use the next lower detail category for transverse butt weld in rolled section made of galvanized steel, i.e., detail category 80 with $m=3.00$.

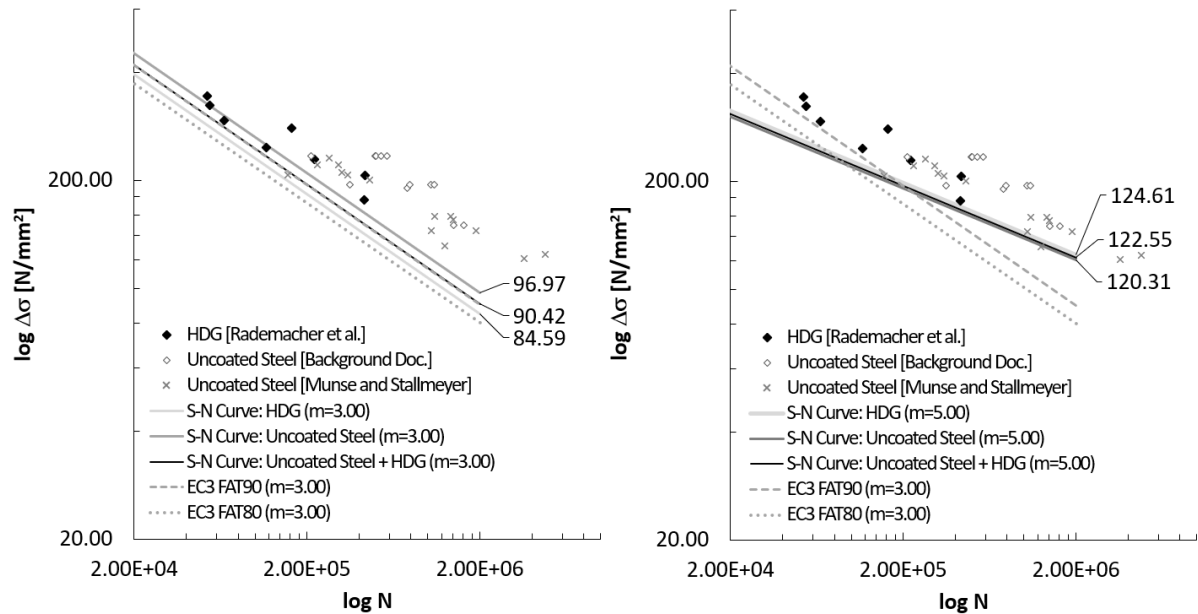


Figure 9- Statistical evaluation: screened tests for transverse butt weld in rolled section.

4.8 Stud shear connectors for composite application

In Figure 10, the fatigue data by Rademacher (Rademacher, 2017) was complemented with 2 studies on uncoated steel from the background documents for EN 1993-1-9 (prEN 1993-1-9, 2003; Brozzetti, et al., 1989). When considering the fatigue data for HDG details, the detail category only reaches 85. Here again, this S-N curve was derived from an unscreened statistical population. When excluding data points that seem not to follow the trend of the combined statistic population, the current detail category, i.e., 90 can be safely kept. To simplify the EN 1993-1-9 (EN 1993-1-9, 2005) approach, the authors are not in favour of changing the rules for HDG details. One would want to have more test results to justify amending the code for HDG specimens.

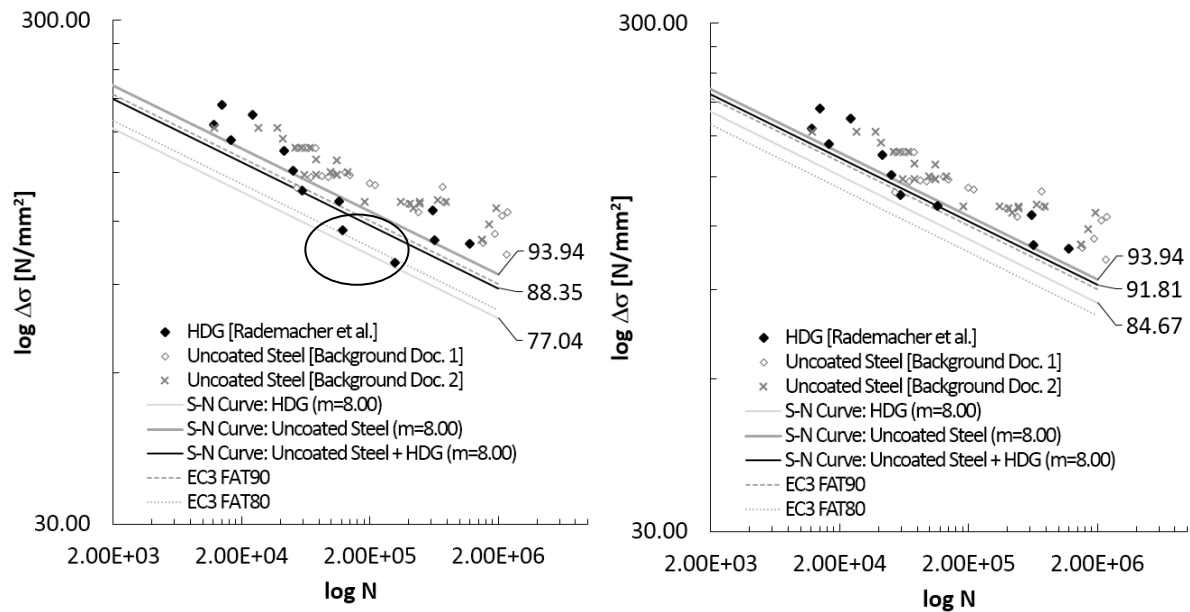


Figure 10- Statistical evaluation: stud shear connectors for composite application.

5 CONCLUSIONS

This paper comprises meta-analysis of fatigue testing data for HDG steel details together with uncoated steel, aiming to establish fatigue categorizations based on existing datasets. Quite a lot of research effort has been put on the development of S-N curves for fatigue verifications, however, the fatigue test data found in the literature are shown to be usually inconsistent.

Eight fatigue details were re-analysed in this paper. Based on the review, it was demonstrated that the new set of rules presented in the draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020) is valid for the majority of the HDG steel details. These rules and the proposal for HDG steel details are summarized in Table 3. Therefore, hot dip galvanizing has not such a detrimental effect that, the rules for HDG steel details should be differentiated at the core. The main conclusion are as follows:

- The S-N curves for uncoated and HDG steel should be amended according to the draft revision of EN 1993-1-9 (prEN 1993-1-9, 2020), as a better correlation with the experimental data can be achieved with a slope $m=5.00$ for plain members as well as bolted connections.

This positive development has a significant influence on the interpretation of the data for HDG details, resulting in fewer adjustments to the detail categories.

- A slope $m=5.00$ should be used for flush-ground butt welds, as both uncoated and HDG steel specimens failed to meet the category proposed by the code. Furthermore, one would expect the slope of this detail to be modified to $m=5.00$ in the revision of EN 1993-1-9 (prEN 1993-1-9, 2020), similarly to plain steel members, as the geometrical imperfections are removed this detail. When keeping the slope $m=3.00$, a note should be added to the EN 1993-1-9 (prEN 1993-1-9, 2020), suggesting the use the next lower detail category for flush-ground butt-welded plate specimens made of galvanized steel, i.e., detail category 100 with $m=3.00$.
- The fatigue tests concerning transverse butt weld in rolled sections made of HDG steel failed to meet the category propose in EN 1993-1-9 (prEN 1993-1-9, 2020). However, when using $m=5.00$, the detail category may be maintained. Alternatively, a note should be added to the EN 1993-1-9 (prEN 1993-1-9, 2020), suggesting the use the next lower detail category for transverse butt weld in rolled section made of galvanized steel, i.e., detail category 80 with $m=3.00$.
- Considerable deviations were found when comparing HDG fatigue data of different authors, for both bolted connections with preloaded bolts and fillet welded cruciform specimens made of HDG steel. Therefore, the HDG data related to these details should not be combined when deriving conclusions, as there might be problems related to the experimental procedures, or the quality of welds. The authors are not in favour of changing the rules for HDG details. However, more fatigue tests are desirable to support keeping the suggested detail categories.

Ultimately, when adopting a different slope m for fatigue assessment of road bridges, the damage equivalence factors given in section 9.5.2 (4) to (7) of EN 1993-2 (EN 1993-2, 2006) should be calculated using exponents 4 and 0.25 in place of those given. For railway bridges, the

damage equivalence factors should be calculated according to the Annex NN of EN 1992 2 (EN 1992-2, 2005) but using instead the exponent $k_2=4$. The authors suggest a comparative fatigue analysis, using $m=3.00$ and $m=5.00$, as further research work.

DATA AVAILABILITY STATEMENT

All data generated or used during the study appear in the submitted article.

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