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Increasing residual lifetime of steel structures through use of nanometallic multilayer treatment

Marcus Rutner[a,b,*]

[a]*Hamburg University of Technology, Institute for Metal and Composite Structures, Am Schwarzenberg-Campus 3, 21073 Hamburg, Germany*
[b]*United Nations University Hub on Engineering to Face Climate Change at the Hamburg University of Technology, United Nations University Institute for Water, Environment and Health (UNU-INWEH), Hamburg, Germany*

Abstract

Steel bridges are experiencing premature aging due to fatigue with structural connections particularly affected. According to the International Institute of Welding (IIW), welded connections deteriorate because of inherent geometric notches as well as material changes that occur during the welding and cooling process. Researchers at Hamburg University of Technology have developed a novel post-weld treatment known as nanometallic multilayer (NMM) treatment. This method applies a nanolaminate coating using electrodeposition, covering the entire connection area. Upon solidification, the NMM induces compressive residual stresses in the steel substrate adjacent to the surface, further, acting as a high-strength and ductile layer on the welded area, effectively delaying crack initiation. Recent findings demonstrate a significant increase in fatigue strength of the butt-welded double-V weld from FAT class 80 to FAT class 225, which corresponds to a more than tenfold extension in service life. This study for the first time investigates the potential of NMM technology as maintenance method for existing steel structures. Local fatigue-critical welded joints, which limit the service life of the overall structure, are treated with NMM and significantly increase the residual lifetime of the overall structure. This study presents a quantitative assessment of this residual lifetime increase and underlines the potential in regard to sustainability goals, economic viability and readiness of steel infrastructure.

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Keywords: Residual lifetime; Fatigue; Steel Structures; Infrastructure; Sustainable Design; SDG

* Corresponding author. Tel.: +49-40-30601-3022.
E-mail address: marcus.rutner@tuhh.de

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1. Introduction

Fatigue is highly responsible for premature failure of joints, components and structures and has significant implications for the design and longevity of infrastructure subjected to cyclic loading. Welded joints, which are found in more than half of all civil engineering products (Aucott et al., 2017), are in most cases critical positions where fatigue cracks initiate, posing risks to the structural integrity and functionality of the steel structure. As a result, improving the fatigue resistance of these welded connections is vital for ensuring the longevity and safety of metal infrastructure. The critical point for steel bridges is global fatigue failure at notch details. If the steel bridge is well designed for fatigue, it can achieve a service life of 100 years. The question is, what service life would be achievable if critical notch details did not fatigue. The development of advanced post-weld treatment methods presents a crucial step towards more sustainable and resource-efficient structures. However, traditional post-weld treatments (Kuhlmann et al., 2005; Ummenhofer et al., 2009, 2005) achieved only limited improvement in fatigue strength due to significant scatter of data, thus preventing widespread use of these conventional methods.

A novel post-weld treatment (PWT) has been introduced in the form of a nanostructured metallic multilayer (NMM) applied on the welded (double-V-weld) butt joint (Brunow et al., 2022; Brunow and Rutner, 2021). The effects and implications for the welded monopile foundation of offshore wind energy plants have been explored (Brunow et al., 2023). This paper seeks to investigate the potential of NMM to increase the residual life time of steel infrastructure, such as bridges, when applied on a built steel bridge.

NMM is a surface treatment of the welded joint. Hence, the NMM develops its effect at the surface and adjacent to the surface which are the critical areas in respect to fatigue. Cracks mostly initiate at the surface and propagate into the material. The NMM has a micrometer thickness and does not lead to stiffness change, compared to other strengthening methods, such as Fiber Metal Laminates (Woelke et al., 2015). The NMM thin film does not contribute in carrying any internal forces, but induces compressive stresses at and adjacent to the steel surface suppressing dents and microcracks. Further, the NMM is combined with blast cleaning of the steel surface, which by itself contributes to inserting compressive residual stresses into the surface. The NMM post-weld-treatment has been developed over the last years from small-scale laboratory tests (Brunow and Rutner, 2021; Brunow et al., 2021; Ramezani et al., 2017) to a scalable technology (Brunow et al., 2022) by using electrodeposition, applicable for new and existing structures (Rutner et al., 2024; Rutner et al., 2025; Seidelmann et al., 2025) as well as for metal 3D-printed structures (Falah et al., 2025).

Welding and subsequent cooling causes residual stresses due to warpage, shrinkage, phase transition, grain growth and geometric inhomogeneities (Chmelko et al., 2018; Hensel et al., 2015; Totten, 2008). Conventional post-weld treatments try to change the geometry of the weld by grinding or remelting (Al-Karawi and Al-Emrani, 2021). Alternatively, PWT introduce compressive stresses into the steel adjacent to the surface reducing localized stress concentrations during cyclic loading and thereby enhancing the fatigue performance (Kuhlmann et al., 2005; Ummenhofer et al., 2009). As a third measure, protective coatings shield the weld off environmental conditions.

Electrodepositing a Cu/Ni NMM onto the weld and the HAZ greatly increases the fatigue strength of the connections, as demonstrated before (Brunow et al., 2023). The underlying mechanism is believed to be highly depending on the residual stress states at and adjacent to the surface. Recently, Fazel et al. (2026) describe that, introducing saccharine into the electrodeposition bath causes residual stress state exceeding -155±5 MPa.

This paper presents the theoretically achievable residual service life with NMM according to current research findings and illustrates the theoretical potential of NMM technology in a calculation example of the remaining service life of a welded structural detail of a steel bridge compared to the as-welded connection. The results are discussed in light of the literature regarding the maximum achievable service life of steel bridges and limiting factors.

2. Fatigue due to NMM Post-Weld Treatment

Fatigue testing is performed in a recent study with *as-welded* dogbone samples and with samples after *NMM* deposition, both for *direct current (DC)* and *pulsed current (PC)* plating (Spalek, Fat2025). The dog-bone samples have the dimensions 280x25x8 mm^3 and are in accordance with (*DIN 50125:2022-08*, 2022) sample type E. The S355

J2 mild steel samples are centrally welded together using Böhler Q G3Si1/SG2 as filler material. Tensile-tensile fatigue testing is performed and evaluated according to (*DIN 50100:2016-12*, 2016) on a servo-hydraulic uni-axial testing machine (Schenck PC400M) with a frequency of 8 Hz and stress ratio R=0. Before deposition of the NMM, a special sample pre-treatment removes any oxides, scales, contamination or grease. In the following, two sample sets are distinguished, the sample set *DC NMM* and the sample set *PC NMM*. For sample set *DC NMM*, surface pre-treatment is performed via abrasively grinding the samples with grit 80 to a metal shine finish followed by ultrasonic cleaning before electrodeposition of the NMM. In contrast, sample set *PC NMM* is clean blasted using steel spheres (S110 by MHG) with 6.5 bar to remove any residue followed by ultrasonic cleaning and electrodeposition of the NMM.

Electrodeposition is controlled by a galvanostat pulse plating power supply (Plating Electronics pe86CB-20-5-25-SGD). The Ni/Cu sulphate-based electrolyte according to Bonhôte and Landolt (1997) is used in a single-bath configuration to achieve a multilayered cross section by controlling the current densities and deposition times of the respective nanolayers. A total thickness of 9000 nm is deposited, consisting of a 1000 nm Ni-base layer for optimal adhesion between the steel-based substrate and the multilayered Copper and Nickel films. While for *DC NMM* a direct current is applied for each layer, for *PC NMM* the current is supplied in high-frequency pulses. Detailed information about the electrodeposition parameters is summarized in Spalek et al. (2025).

Energy Dispersive X-Ray Diffraction (EDXRD) is performed at the P61A white beam beamline of PETRA-III at DESY in Hamburg.

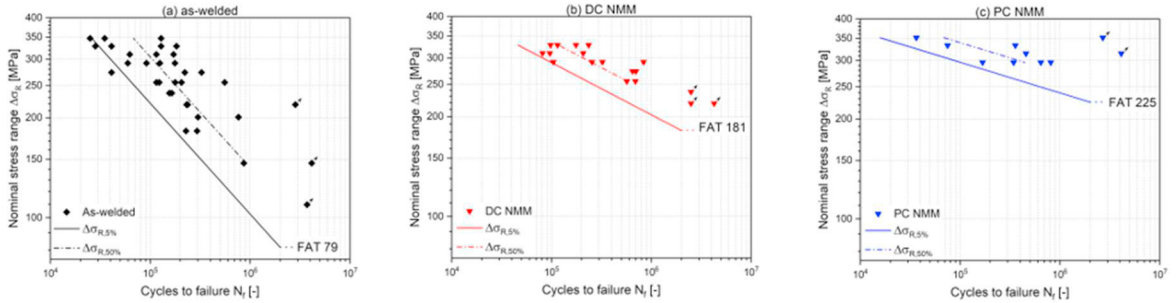


Fig. 1. S-N curves and their mean (dashed line) and 5%-quantile (solid line) for sample sets (a) As-welded, (b) DC NMM and (c) PC NMM. Annotation of their respective FAT classes (Spalek et al., 2025).

The S-N curves for the mean (dashed lines) $\Delta\sigma_{R,50\%}$ and the 5% quantile (solid lines) $\Delta\sigma_{R,5\%}$ are shown in Fig. 1. Run-outs are considered samples exceeding 2.5×10^6 cycles to failure. The slope of the S-N curve of the *as-welded* sample set is set to k = 3 in accordance with (*DIN EN 1993-1-9*, 2010). The resulting fatigue strength is 79 MPa, hence, consistent with the FAT class of the DV butt-welded joint of 80. In the welding notch class catalogue of *DIN EN 1993-1-9*, the highest FAT class 160 corresponds to the base material. The fatigue tests of the *DC NMM* data set yields to an increased FAT class of 181, far exceeding conventional post-weld treatments (Haagensen and Maddox, 2013; Marquis and Barsoum, 2016), as shown in Fig. 1(b). The notable decrease in inherent variance, as illustrated by the reduced scatter of data points, has contributed to the elevation of the FAT class. The reduced scatter, hence the smaller distance between the mean $\Delta\sigma_{R,50\%}$ and 5%-quantile $\Delta\sigma_{R,5\%}$, is interpreted as a high level of reproducibility and reliability of the NMM technology. The slope of the S-N curve is reduced to m = 6.3, confirming lower fatigue-criticality of the NMM post-weld treated weld compared to the *as-welded* condition. More data are needed to verify the exact endurance limit, however only run-outs are detected at nominal stress levels below 0.7 f_y, as shown in Fig. 1(b).

For the sample set *PC NMM* the fatigue data show an even further increased FAT class 225, exceeding the results of the *DC NMM* sample set. The slope is reduced to m = 10.8. More data are needed to confirm the endurance limit.

Surprisingly, run-outs are observed for stress levels up to 90% of the yield strength f_y of the substrate steel.

3. X-Ray stress analysis

In Brunow et al. (2023) hypotheses for the underlying mechanisms for increased lifetime are presented, with a particular focus on residual stresses. Spalek et al. (2025) explore the influence of the compressive residual stresses (RS) in the steel substrate through combined clean blasting and NMM in detail. The redistribution of residual stresses mitigates notch criticality in the weld toes. In order to verify the hypothesis, EDXRD measurements are conducted, to measure and quantify the residual stress distribution across the depth and adjacent to the surface. Fig. 2 presents the residual stresses across the thickness in the steel substrate. The residual stress distribution in the s_{11}-direction of the *as-welded* condition is not uniform but varies. *PC NMM* treatment leads to a significant enhancement in the compressive stress profile. This enlarged profile extends to a depth of $d_{PC,0}$ = 157 µm into the steel substrate. The highest residual compressive stress is measured at the surface of the steel substrate and amounts to $\sigma_{11,\text{ PC NMM, min}}$ = -650 MPa.

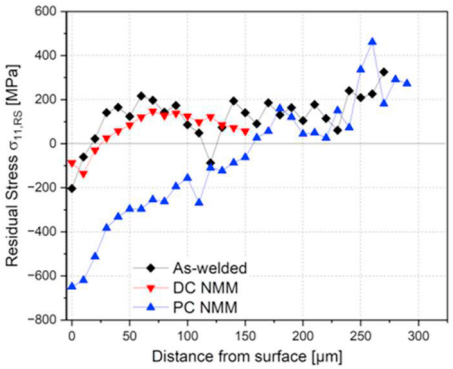


Fig. 2. $\sigma_{11,RS}$ Residual stress gradient across the depth of the sample (Spalek et al., 2025).

4. Calculation of remaining service life according to DIN EN 1993-1-9

According to DIN EN 1993-1-9, the nominal stress range $\Delta\sigma_{E,2}$ is determined as the standard method for the structural analysis of steel bridges. The verification is then carried out according to Eq. 1.

$$\gamma_{Ff} \cdot \Delta\sigma_{E,2} \leq \frac{\Delta\sigma_c}{\gamma_{Mf}} \tag{1}$$

Since the notch fall classes ($\Delta\sigma_c$) in Eurocode are always defined for 2 million cycles, the $\Delta\sigma_{E,2}$ value allows a direct comparison and summarizes all the different load changes from the real traffic train in a single, fictitious value that causes the same damage. For bridges, the damage equivalent factor λ is determined to capture load collectives, Eq. 2.

$$\Delta\sigma_{E,2} = \lambda \cdot \Phi \cdot \Delta\sigma_p \tag{2}$$

$\Delta\sigma_p$ is the stress amplitude from the ideal load model (e.g., load model 3 of EC 1). λ is the damage equivalent factor, which takes into account factors such as traffic volume (λ_1), service life (λ_2), damage relevance (λ_3), and multi-lane configuration (λ_4).

To calculate the remaining service life of an existing bridge, the $\Delta\sigma_{E,2}$ approach is particularly helpful for converting different traffic periods into a comparable value.

The proportional damage D (according to Palmgren-Miner) is calculated from the nominal stress range $\Delta\sigma_{E,2}$ by referring to the experimentally determined S-N curve. The calculated damage D for a given period (e.g., one year or the entire service life) is derived from Eq.3.

$$D = \left(\frac{\gamma_{Ff} \cdot \Delta\sigma_{E,2}}{\frac{\Delta\sigma_C}{\gamma_{Mf}}} \right)^m \cdot \frac{n_{ist}}{2 \cdot 10^6} \tag{3}$$

The components of Eq.3 are:

1. The applied nominal stress range ($\Delta\sigma_{E,2}$) is related to the characteristic reference value $\Delta\sigma_c$ for the fatigue resistance at $2 \cdot 10^6$ cycles.
2. For $\Delta\sigma_{E,2}$, the exponent of the S-N curve for structural steel details $m = 3$ is used.
3. The number of load cycles (n_{ist}) that actually occur during the period under consideration (e.g., the number of trucks per year) is taken into account
4. The partial safety factors γ_{Ff} (load side) and γ_{Mf} (material side) are considered in accordance with Eurocode specifications.

The remaining service life L_{rest} is calculated by using the load cycles N based on the damage as follows.

$$N = 2 \cdot 10^6 \cdot \left(\frac{\Delta\sigma_c}{\Delta\sigma_{E,2}} \right)^m \rightarrow L_{rest} = \frac{N}{2{,}000{,}000} \; [years] \tag{4}$$

Weld post-treatment using NMM improves fatigue behavior, which can be captured by Eqs. 1-4. The following effects are considered:

1. Higher FAT class, represented by characteristic reference value $\Delta\sigma_c$

By smoothing the weld transitions and introducing compressive residual stresses, the FAT class increases (e.g., from FAT 80 to FAT 225, as determined by Spalek et al. (2025)). Since $\Delta\sigma_c$ is in the denominator of the damage equation, the damage value D already decreases linearly due to the higher fatigue strength of FAT class 225.

2. S-N Curve with reduced gradient (Larger m)

The flatter S-N curve is the crucial factor. Even though Spalek et al. (2025) determined a gradient of $m = 10$, $m = 7$ is picked to be conservative. Since the stress ratio is calculated using the power of m, any reduction in load or increase in resistance has an extremely strong effect (DASt Guideline 026). At $m = 7$, halving the stress not only results in 1/8 of the damage (as with $m = 3$), but in 1/128 (=0.0078).

The total damage D decreases significantly because a) the difference between the applied stress ($\Delta\sigma_{E,2}$) and the resistance ($\Delta\sigma_c$) increases; and b) the sensitivity to load cycles decreases due to the higher exponent m.

A changed exponent (e.g., $m = 7$) also requires a recalculation of the damage equivalent factor λ, since standard damage equivalent factor λ in Eurocode are derived based on $m = 3$. The damage equivalent factor λ for $m = 7$ ($\lambda_{m=7}$) can be derived as follows:

$$\lambda_{m=7} \approx (\lambda_{m=3})^{\frac{3}{7}} \tag{5}$$

Since λ in bridge construction is usually between 0.5 and 2.5, raising it to the power of 3/7 = 0.43 results in a smaller damage equivalent factor λ. A smaller λ means a lower nominal stress range $\Delta\sigma_{E,2}$, which significantly increases the service life.

5. Example calculation for a road bridge according to DIN EN 1993-1-9

A typical combined damage equivalent factor λ (from λ_1 to λ_4) of 1.2 (based on $m = 3$) is assumed:

- Standard ($m = 3$): λ =1.2
- The adjusted damage equivalent factor is (m=7): $\lambda = 1.2^{0.43} \approx 1.082$

With a flatter curve (m =7), the statistical effect on stress amplitudes is less pronounced. Since a load collective in bridges consists of many small and a few large loads, the overall damage potential (λ) is lower at a higher exponent.

This section uses a practical example of a critical detail on a steel road bridge (e.g., a welded crossbeam connection).
- Notch class: FAT 80 ($\Delta\sigma_c = 80$MPa at $2 \cdot 10^6$ cycles).
- Standard exponent: $m = 3$
- Loading: An assumed load value $\Delta\sigma_p = 60$MPa and a combined damage equivalent factor $\lambda_{m=3} = 1.2$
- Partial safety factors: $\gamma_{Ff} = 1.0$ and $\gamma_{Mf} = 1.0$ are set to ease comparability.

Thus, the nominal stress range and the corresponding utilization factor are determined to be $\Delta\sigma_{E,2} = 1.20 \cdot 60 = 72$MPa, and utilization factor $= \frac{72}{80} = 0.90$, respectively.

High-quality post-treatment with NMM improves the notch case to FAT 225 ($\Delta\sigma_c = 225$MPa), and the S-N curve becomes flatter (conservatively set $m = 7$).

The adjusted damage equivalent factor λ yields $\lambda_{m=7} = 1.2^{3/7} = 1.082$.

The nominal stress range is calculated to be $\Delta\sigma_{E,2} = 1.082 \cdot 60 = 64.89$MPa.

From this, the damage share is calculated as follows:

- Damage of *as-welded state* ($m = 3$): $D_{as-welded} = \left(\frac{72}{80}\right)^3 \cdot \frac{2 \cdot 10^6}{2 \cdot 10^6} = 0.73$
- Damage after *NMM treatment* ($m = 7$): $D_{NMM} = \left(\frac{64.89}{80}\right)^7 \cdot \frac{2 \cdot 10^6}{2 \cdot 10^6} = 0.23$

For this calculation of the remaining service life, a realistic load is assumed for a heavily traffic German motorway bridge (corresponding to traffic category 1 according to Eurocode 1): The annual number of trucks (n_{Jahr}) = 2,000,000 trucks per lane. The comparison of the calculated remaining service lives is as follows:

Case 1. Standard weld (as-welded)
- Values: FAT 80, $m = 3$, $\Delta\sigma_{E,2} = 60$MPa
- Calculation of the allowable number of load cycles (N):
  $N = 2 \cdot 10^6 \cdot \left(\frac{80}{72}\right)^3 = 2{,}743{,}000$ cycles
- Remaining service life in years:
  $L_{rest} = \frac{2{,}743{,}000}{2{,}000{,}000} \approx 1{,}4$ years

The component is therefore, from a computational standpoint, at the end of its service life.

Case 2: Weld treated with NMM ($m = 7$)
- Values: FAT 225, $m = 7$, $\Delta\sigma_{E,2} = 64.89$MPa (adjusted λ)
- Calculation of the allowable number of load cycles (N):
  $N = 2 \cdot 10^6 \cdot \left(\frac{225}{64.89}\right)^7 = 12{,}052{,}000{,}000$ cycles
- Remaining service life in years:
  $L_{rest} = \frac{12{,}052{,}000{,}000}{2{,}000{,}000} \approx 6{,}029$ years

Through the combination of higher strength (FAT 225) and the flatter exponent (m = 7), the calculated remaining service life increases from a critical condition (just over 1 year) to a level that theoretically far exceeds the design service life of bridges (100 years). The result indicates that the welded detail treated with NMM is no longer fatigue-critical. This value should be regarded as a theoretical result. For practical applications, it is crucial that the post-treatment is only effective at the treated location. The critical point therefore shifts to the next untreated structural detail. Post-treatment of all fatigue-critical details - assumed that NMM treatment is equally effective for different notch cases - could theoretically lead to an increase in fatigue strength beyond that of non-welded structural details (Rutner et al., 2024 and Rutner et al., 2025).

In reality, however, other factors limit the service life, for example:

- Changed load models: Bridges constructed around 1900 are not designed for 40-ton trucks. Thus, even in the absence of fatigue, purely static safety (safety factors) would often no longer be sufficient today.
- Geometry: Roadway widths, curve radii, and clearance heights no longer meet modern standards.
- Embrittlement: Older steels (e.g., wrought iron or mild steel) may become brittle over decades due to nitrogen embrittlement.

Literature states that, once notch effects are eliminated, the limiting factor for service life is no longer fatigue failure but rather potential economic total loss due to high maintenance costs for corrosion protection. Under ideal conditions, a maximum service life of approximately 200 years is cited (Koh et al., 2014). The oldest steel or iron bridges still in use today are approximately 140 to 160 years old, e.g., parts of the Forth Bridge or early riveted structures in the USA). However, there is no data basis demonstrating that the physical properties of steel remain stable over periods of 200 years or more under dynamic loading (Rakoczy and Otter, 2019). Further research is required. On the one hand, the NMM technology should be applied to aged welded bridge details in order to experimentally determine the remaining service life. On the other hand, welded bridge details should be subjected to combined fatigue and corrosion loading to determine realistic remaining service lives of welded bridge details, thereby enabling reliable statements regarding the use of such structures beyond 200 years.

6. Conclusions

The combined clean blasting and nanostructured metal multilayer (NMM) treatment of the double-sided V butt-welded joint results in a significant increase in fatigue strength. NMM deposited using pulsed current leads to an increase from FAT class 80 (as-welded condition) to FAT class 225, corresponding to an S–N curve slope of approximately 10. Run-outs are observed at a stress range of 80–90% of the yield strength, which may serve as an initial indication of a high endurance limit. These experimental findings are incorporated into the calculation of the nominal stress range, the assessment of accumulated damage, and the determination of residual service life.

An example calculation for a welded bridge detail demonstrates that NMM treatment, preceded by clean blasting, results in remaining service lives that are significantly greater than the originally assumed design life of 100 years.

The oldest steel or iron bridges still in operation today are only approximately 140 to 160 years old. The extent to which this theoretical increase in the remaining service life of individual joints can be transferred to the entire bridge structure remains uncertain. There is no established data basis demonstrating that the physical properties of steel remain stable over several centuries under dynamic loading.

In addition to fatigue of structural details, the literature identifies further factors that may limit service life, such as corrosion, changes in load models, and geometric requirements. However, there is a lack of quantitatively established data on pre-aged welded structural details, as used in bridge construction, that are subsequently treated with NMM, and for which the remaining service life is determined with particular emphasis on fatigue as well as combined fatigue–corrosion loading. This constitutes a clear need for further research.

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