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More durable modular expansion joint constructions for road bridges

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Abstract

Relevant aspects in the design of modular expansion joints are the high fatigue stress caused by heavy load traffic and the corrosion protection. Currently, corrosion damage is often not limited to the traversable surface. Therefore, more durable expansion joints are highly desirable to extend their service life. The FOSTA research project P1574 resulted from the need for durable expansion joints and thus is aimed at hot-dip galvanized structures. In this project about 14.000 individual damages on 6.300 modular expansion joints were evaluated, relevant hot-dip-galvanizing parameters were investigated and recommendations for hot-dip galvanizing-compatible constructions were made. In addition, the fatigue strength of existing constructions has been evaluated with regard to the current and upcoming version of Eurocode 1993-1-9. This evaluation will be verified in the course of cyclic tests and numerical investigations. A monitoring concept is to be designed according to the requirements of the modular expansion joints and the corresponding neuralgic points.

Keywords

modular expansion joint, road bridges, corrosion protection, hot-dip-galvanizing, organic coating

1 Introduction

Due to the strong dependence of today's economy on the road network, the importance of securing the availability of transport routes and therefore guaranteeing mobility in the future significantly increases. Maintenance measures are known to repeatedly lead to lane relocations or even road closures and thus to high economic costs. As a result, it is necessary to thoroughly analyze and further develop frequently endangered components of bridges, including expansion joints. They are important components of bridges as they are essential to a safe crossing.

Modular expansion joints and expansion joints in general are used to bridge the structural joints in bridge construction. They can vary in width and length due to movements caused by temperature changes in the bridge superstructure, creep and shrinkage of the concrete, support settlement and uplift as well as traffic loads. In order to ensure a safe crossing even with large movement ranges, modular expansion joint constructions are the favored solution in such cases. This system consists of directly traversable lamellae running transversely to the carriageway and longitudinal crossbeams that serve as supports for the lamellae and transfer the loads into the superstructure or the support (see Figure 1).

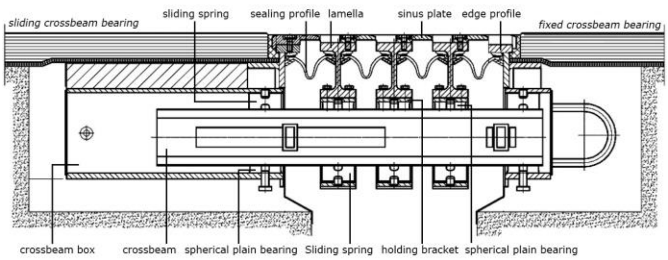

Figure 1 Commented section of an exemplary modular expansion joint construction. Source: mageba sa

For the latter, either I-profiles or solid rectangular steel cross-sections are used, while the lamellae are special elements in the form of I-profiles with claws on the web. The elastomer sealing profiles between the lamellae are clamped into these claws, deformed as a result of the longitudinal displacement of the expansion joint and ensure

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the watertightness of the construction at the same time. They serve as a boundary between the superstructure and substructure. The washboard-like surface caused by the parallel lamellae results in increased noise when crossing. In this case bolted or welded noise reduction elements can provide a suitable solution.

2 Current issues

2.1 Limited lifespan

Expansion joints are designed in accordance with European Technical Approval Guidelines (ETAG) 032-1 Section 2.3.4 [1] and EAD 120113-00-01073 1.2.2 Table 1 [2] for a service life of up to 50 years. There are hardly any reports of heavily trafficked expansion joints which achieve this goal. Rather, it is the case that corrosion damages occur after just a few years in operation and costly repair work has to be carried out, often during the five-year warranty phase. Critical locations are the low points where water can accumulate. The lowest points and the construction site joints of the lamellae sometimes coincide in the centre of the superstructure, meaning that leaks can cause the most damage at this point by abusing imperfections of welded and bolted connections.

Experience has shown that the major problem of expansion joints is their short service life. In the case of components subject to wear, it is quite obvious that major repair work will have to be carried out in the course of the structure's life cycle. However, the frequently carried out measures often exceed the work that could be described as ordinary and expected. For example, in addition to the elastomer sliding bearings or springs and EPDM seals to be replaced as expected, in some cases entire expansion joints have to be exchanged because the structure is damaged due to corrosion or fatigue. The replacement of a damaged expansion joint includes the removal of the old expansion joint as well as the production and installation of a new one. Therefore, it is not uncommon for poorly constructed structures to cost three or four times the original acquisition cost of the expansion joint over the lifetime of the bridge.

2.2 Corrosion protection with organic coatings

The currently most common type of coating is the organic coating. It can be applied cost-effectively over large areas and in an even manner, but only offers a limited service life under adverse conditions. The durability of organic coatings can only be guaranteed for 8 to 25 years, depending on the climatic and atmospheric conditions. Experience has shown that organic coatings in accordance with ZTV-ING 4-3 A Table A 4.3.2 [3] often do not achieve the criteria of high protection period class (>15 years). In the case of coated lamellae, which are subject to traffic of thousands of vehicles every day, the organic coating in the traversable area is expected to be completely worn down in just a few weeks' time. As anticipated, there is a correlation between traffic volume and the wear of the coating [4]. In certain areas this is usually not a cause for concern, as the corrosion products that have accumulated are removed with each crossing for the steel to be blank again. Therefore, extensive corrosion of the surface is almost impossible.

The front or contact surface between the sealing profile and lamella or edge profile is much more relevant than the surface on the top flange, as chipping and heavy wear of the coating on the side or the exposed edges of the lamellae and edge profiles can cause water and moisture to run behind the coating on the front surfaces and initiate corrosion underneath the organic coating. This can also occur through hairline cracks in the coating. The process is also known as under-rusting. Particularly at the critical point of the claw, this can lead to leaks, which subsequently have serious consequences for the substructure.

During repair work, it is not always possible to restore the coating to a satisfactory extent. The clamping profiles are cleaned, then given a primer coat and finally painted with the top coat. It cannot be assumed that this coating will match the quality of a factory-applied corrosion protection. The problem of corrosion protection of expansion joints has therefore not yet been solved adequately with conventional organic coatings.

3 Damages on expansion joints

Damages on expansion joints, which can be documented in accordance with the German RI-EBW-PRÜF [5], for example, can be divided into three main categories. Fatigue damages can be summarized in the first category, corrosion and coating damages in the second and any functional damages are compiled in the third category.

Damages of fatigue result from use and the corresponding wear. They are favored by recurring high loads and irregular, too superficial maintenance or monitoring. Examples of wear-related damages are crossbeam or lamella fractures, chipping of coatings (see Figure 2) as well as deformation of the lamellae, defective sliding plates and spring bearings, sliding bearings and sliding springs that have fallen out.

Figure 2 Heavy accumulation of dirt; chipping and flaking of the organic coating. Source: IKS Dresden GmbH

System-related damages arise from the actual purpose of the construction. For example, watertight systems are intended to protect the substructure from moisture, but are susceptible to soiling and clogging of the sealing profiles between the lamellae (see Figure 2), which in turn can result in restricted movement of the lamellae or loosening of the sealing profiles. Noise reduction elements impede the self-cleaning capability often attributed to modular expansion joints in exchange for a quieter transit. System-related damage also includes corrosion damages (see Figure 3) that occur as a result of leaks in the sealing profiles themselves or under-rusting.

Figure 3 Heavily corroded lamellae and scissor mechanism. Source: Author

In the research project a comprehensive dataset of recorded damages was provided by the German Building Authority for the investigations into damages on modular expansion joints. The available data included 14.029 individual cases of damage to 6.291 expansion joints on 3.887 (partial) structures. The data contained information on the structure, the component (in this case the expansion joint) and the corresponding damages. The latter were documented with a description, localization and an evaluation regarding its impact on stability, durability and traffic safety assessed by the inspection engineer. Due to the subjective nature of bridge inspections and the way the damages have to be input into a German software (SIB-Bauwerke) using only a set number of exemplary damages from a catalog, the data had to be slightly modified. Modifying in this case means to match a given damage description to its correct example and adding 6 new examples to account for all depicted damages. After discussing the addition with inspection engineers an application to expand the current exemplary damages has been filed with the corresponding authority and working group. The inclusion of these would make it easier for inspection engineers to document and assess expansion joints in their entirety.

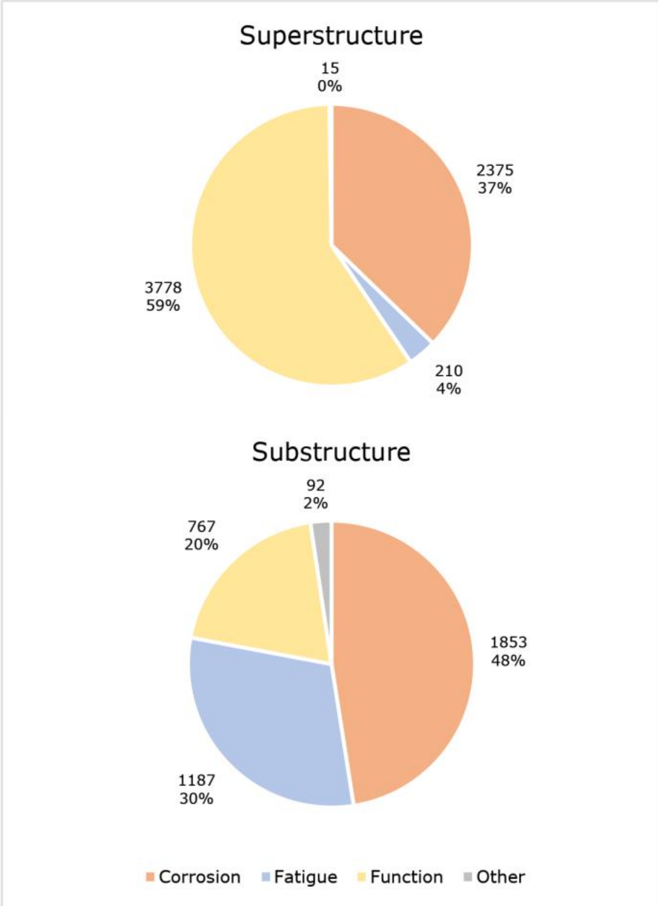

Figure 5 Number and portion of damages at the super- and substructure of modular expansion joints. Source: Author

As a result of the investigation, it is evident that corrosion is the most frequent single form of damage. Combined with damages of the coating, the corrosion-related damages add up to around 40 % (see Figure 4). This is the case for the super- as well as the substructure (see Figure 5). This illustrates the importance of an adequate corrosion protection all round for these heavily exposed components and how the currently used organic coatings are an insufficient corrosion protection.

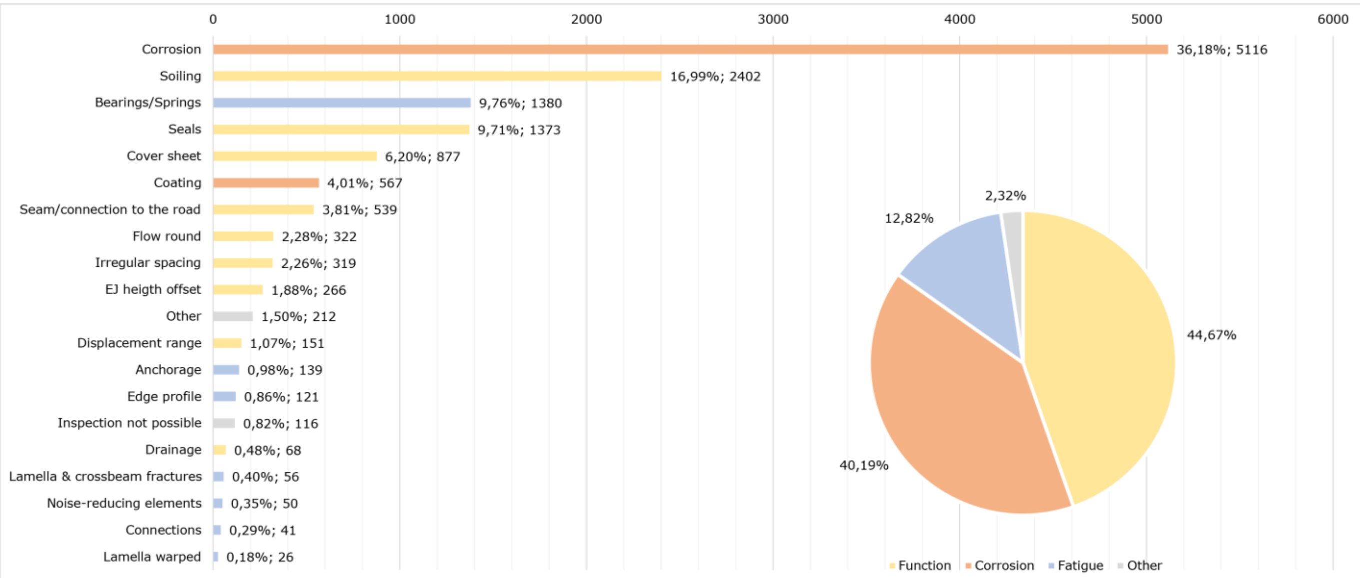

Figure 4 Number and portion of damages on modular expansion joints. Source: Author

4 Corrosion protection with hot-dip-galvanizing

In the corrosion protection process of hot-dip-galvanizing, steel components are given a metallic coating by immersing them in a liquid-hot zinc bath. In addition to EN ISO 1461 [6], which specifies minimum zinc coating thicknesses, EN ISO 14713 [7] specifies the relationship between the chemical composition of the steel and the zinc coatings. DASt Guideline 022 [8] also applies to hot-dip galvanized steel structures for construction supervision purposes and contains recommendations for prevention of cracking during hot-dip galvanizing. Galvanized components are classified in construction classes I-III depending on the components heights, the steel grade and the minimum ductility requirement. The details of the components are then classified in detail classes A-C. The construction and detail classes are used to determine the confidence zone that can be utilized to verify the dwell time in the zinc bath [8] in order to minimize the potential risk of liquid metal cracking (LMC). In addition, galvanizing-compliant design helps avoid engineering structures that are succeptible to excessive distortion due to elongation and temperature stresses in the zinc bath.

The aforementioned required corrosion protection period of up to 50 years according to [1, 2] can be achieved with hot-dip galvanizing. The required zinc coating thickness is calculated using equation (1) or (2) on the basis of a theoretical total wear D according to ISO 9223 [9] and ISO 9224 [10] depending on the corrosivity category (r_{corr}) and a material-dependent time exponent b as well as the expected lifetime t (see Table 1). According to ZTV-ING Table A.4.3.2 row 3.4.2 [3], corrosivity category C5 is currently to be assumed.

$$\mathrm{D}\,(t) = r_{corr} \cdot t^{b} \qquad (1)$$

$$\mathrm{D}\,(t \geq 20) = r_{corr} \cdot [20^{b} + b \cdot 20^{b-1} \cdot (t-20)] \qquad (2)$$

Table 1 Required zinc coating thickness for 50 years of corrosion protection of Sebisty and high-silicone steel for corrosivity categories C4 - CX according to ISO 9223 [9] and 9224 [10]

Category		C4			**C5**		CX
r_{corr} [µm/a]		2,10	3,15	4,20	6,30	8,40	16,77
Sebisty-area							
D (t)	$b_{50\%}$	63,89	95,83	127,78	**191,66**	255,55	510,19
	$b_{95\%}$	80,79	121,19	161,58	**242,37**	323,16	645,17
D (t>20)	$b_{50\%}$	66,30	99,46	132,61	**198,91**	265,21	529,48
	$b_{95\%}$	82,45	123,68	164,90	**247,36**	329,81	658,44
High silicone-area							
D (t)	b_{lin}	105,00	157,50	210,00	**315,00**	420,00	838,50

The verification of the actual corrosivity category, taking into account the microclimates in the area of the expansion joints, is part of the ongoing research project FOSTA P1574. Standard test specimens are used for this purpose. Both coils and plates made out of steel and zinc are placed at the critical points of interest. These include low points where water and all its impurities can collect (see Figure 6), the area of spray mist next to the roadway (see Figure 7) and the area in the abutment beneath the expansion joint (see Figure 8). The special feature of the low points is that they are sometimes closed off with cover plates. Therefore, ventilation is mostly prevented. This is where the greatest corrosivity is expected. The rate of wear of the steel and zinc standard test specimens is determined in parallel with environmental measurements. All test specimens are exposed for 1 year at each of the three chosen sites.

Figure 6 Coils installed underneath a cover plate. Source: IKS Dresden GmbH

Figure 7 Coils and plates installed on a weather stand. Source: IKS Dresden GmbH

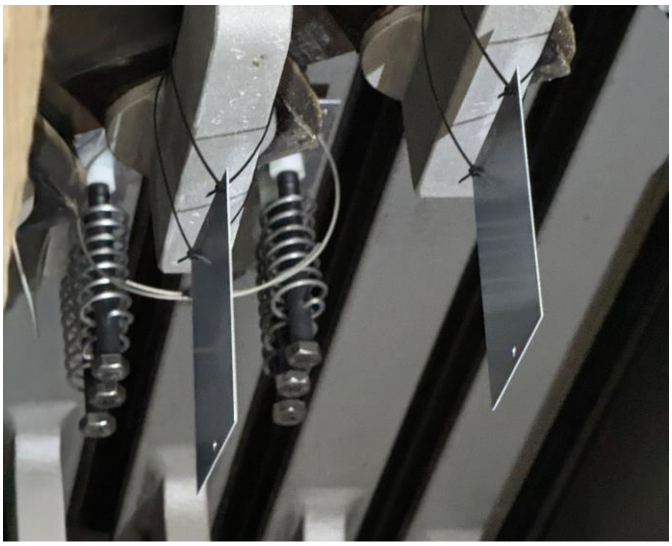

Figure 8 Coils and plates installed in the abutment beneath the expansion joint. Source: Author

Due to the way the metallic zinc coating protects against corrosion, hot-dip galvanizing requires a dry and well-ventilated storage environment. The process of converting zinc hydroxides to zinc carbonate can only take place under those conditions. If the freshly galvanized surface comes into contact with moisture and is also poorly ventilated so that there is hardly any carbon dioxide present, the reaction to zinc carbonate cannot take place. Instead a white layer of zinc hydroxide forms, which is known as white rust. The consequences range from a slight reduction in the thickness of zinc coating to a reduction in adhesion, which is critical for the application of further coatings (duplex-systems), to local destruction of the coating. The extent of the damage should always be assessed by measuring the remaining zinc coating thickness and the prevailing corrosion conditions. When selecting parts from storage, care should be taken to ensure that components of the same batch are used whenever possible. This applies to the material, the zinc bath and the post-treatment or storage, as two supposedly similar components can react differently. White rust can be removed manually with a nylon brush, warm water and some soap.

A zinc paste can be applied to other damages that require the zinc coating to be repaired. On modular expansion joints such defects can occur, for instance during transport or while attaching the sealing profiles. The application of zinc pastes or zinc flake coatings is classified among the use of zinc dust coating materials, which according to DIN EN ISO 1461 [6] is an effective method of repair as is thermal spraying combined with the application of a sealant. On site however, the paste is recommended due to its simple and practical application with a brush. The disadvantage of zinc dust coating materials is the short protection period of 10 to 20 years, especially when compared to thermal spraying. After consultation with bridge owners, the use of zinc solders and zinc sprays should be avoided altogether. The aforementioned generally harmless aspect of mechanical abrasion on the flanges applies equally to galvanized surfaces. In fact, the zinc and iron-zinc alloy coatings have a higher abrasion resistance than the organic coating and therefore offer another benefit in addition to the cathodic corrosion protection. The zinc coating thickness measurement in the traversable area of a 20-year-old modular expansion joint with a duplex-system showed an average remaining zinc coating thickness of around 30 µm, proving its durability, even on a highway (see Figure 9). Measurements on intact areas indicate an original zinc coating thickness of 350 µm.

Figure 9 Mechanical wear of a duplex system. Source: Author

5 Cyclic large-scale tests

The application of hot-dip galvanizing in bridge construction was delayed due to the lack of knowledge regarding its durability and the influence on fatigue resistance. In the FOSTA project P835 (IGF 351 ZBG) [11], it was scientifically proven for the first time at European level through cyclic tests that hot-dip galvanizing is suitable as corrosion protection for steel and composite bridges and that the fatigue strength can be designed in accordance with EN 1993-1-9 [12]. A slight decrease in the fatigue strength of hot-dip galvanized compared to non-galvanized steel components in the case of high notch details was confirmed, and a slight reduction of the galvanized notch details was suggested. After metallographic investigations, it is assumed that microcracks in the iron-zinc alloy layer (δ_1 phase) and a skipping of the initial defect from the zinc layer into the base material are the causes of reduction in fatigue strength [11].

As the lamella profiles and the lamella/beam connections are special constructions that are not covered by the notch catalog of EN 1993-1-9 [12], tests on galvanized and ungalvanized samples are planned for comparability and evaluation of the influence of galvanization. The fatigue strength of galvanized and ungalvanized components can be assessed according to EN 1993-1-9 [12] and the research results from [11] for the crossbeams, for which rolled beams or welded, I-shaped steel cross-sections are generally used. The component tests therefore also focus on the connection of the lamellae to the crossbeams, for which each manufacturer has developed special designs using welded stirrups or bolted brackets.

Given the dominant bending load M_y from the axle loads of heavy vehicle traffic, the fatigue tests of the lamellae are designed as four-point bending tests (see Figure 10) in such a way that the governing notch detail is tested in the unfavorable tensile stress range. Combined V/H loads (in a ratio of 5/1) are also taken into account in order to investigate the influence of driving forces. The fatigue strength of the lamella-crossbeam connection is tested and analyzed under various V/H load combinations as well. The test specimens are tested with varying stress ranges $\Delta\sigma$ until fracture or endurance strength is reached. The statistical evaluation of the tests results in S-N-curves, which are used to define the notch details according to EN 1993-1-9 [12]. At least 4-5 fatigue tests should be carried out for each notch detail. Due to the large deformations that are expected, the cyclic beam tests must be performed at a low frequency of 1-3 Hz, adjusted to the capabilities of the servo-hydraulic testing machine.

Figure 10 Four-point bending test used to evaluate notch details on modular expansion joints. Source: Author

In order to classify the tests carried out, they are compared with tests from literature and their associated S-N-curves. As part of the IGF project 19178 N [13] the notch details of EN 1993-1-9 [12] were statistically re-evaluated and expanded. The data points used in that research project serve as the basis for the comparison of the new test results regarding the base material of the rolled beam (see Figure 11) and the longitudinal weld without stop-starts (see Figure 12).

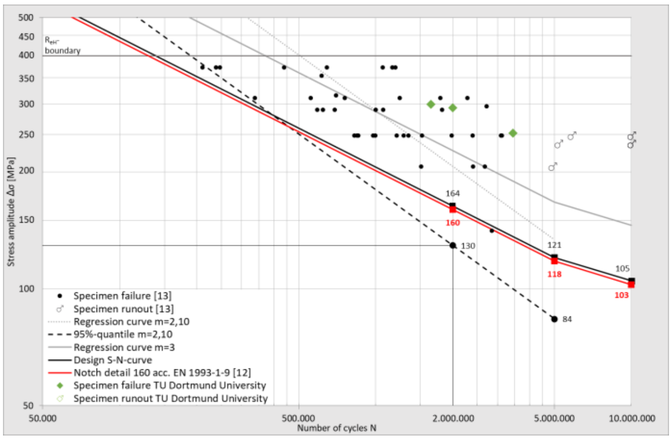

Figure 11 Notch detail 160 from literature and test specimen examined. Source: Author & [13]

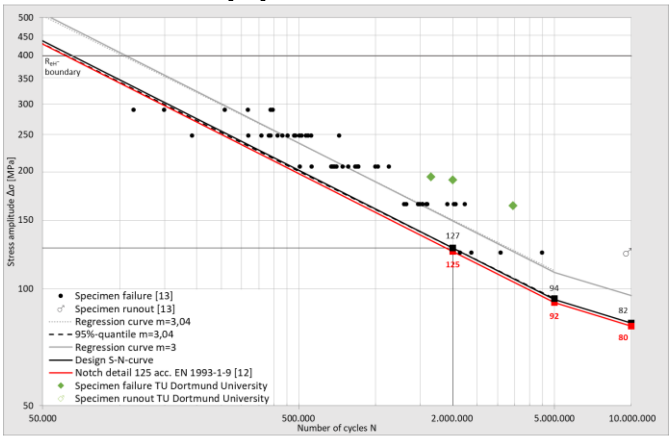

Figure 12 Notch detail 125 from literature and test specimen examined. Source: Author & [13]

6 Outlook

In addition, further cyclic tests to develop the S-N-curves will be carried out. Numerical investigations into the hot spot stress method are planned for both welded and bolted connections. In addition, a monitoring and maintenance concept is to be tested on a modular expansion joint under continuous traffic.

7 Acknowledgement

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