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FATIGUE INDICATORS FOR METAL STRUCTURES: FROM AIRCRAFT TO BRIDGES

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Abstract. The papers focus on a fatigue monitoring method for two types of engineering structures: (a) aircraft and (b) steel bridges. However, the potential application of this new approach extends beyond these examples. It is demonstrated that, despite advancements in stress-strain analysis, improvements in fatigue life prediction methods, and progress in contemporary non-destructive inspection techniques, unexpected failures of metal structures still occur.

This paper outlines the evolution of Fatigue Indicators for Metal Structures, progressing from conceptual development to a family of indicators capable of monitoring fatigue damage in key structural components. These include aircraft parts made of aluminum alloys and load-bearing elements of steel bridges. All the indicators discussed share a unifying concept: the metal surface subjected to cyclic loading reflects accumulated fatigue damage. The primary parameter used to assess this damage is the intensity of the surface deformation relief (extrusion/intrusion patterns), measured using a computer-aided optical method.

The conceptual design of Fatigue Indicators for both uniaxial and biaxial fatigue is explored. The required sensitivity level of the indicators is achieved through the redistribution of the strains by geometric optimization, which is carried out using Finite Element Analysis.

Keywords: aircraft, metal fatigue, alclad alloys, single crystals, fatigue indicator, steel bridges.

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1. Introduction

The first metal fatigue studies refer to the tests of W. Albert, who observed and analyzed the fatigue failure of the steel hoist chains in 1829. A. Wöhler was the first to establish the relationship between cyclic stress versus the number of cycles to failure. The formula proposed in 1910 by O. Basquin describes the fatigue curve for metals under high-cycles fatigue loading. The simple engineering rule for assessing accumulated fatigue damage, initially proposed by Palmgren's (1924) and later further developed by Miner (1945), remains widely used today.

As operational loads on many metal structures have increased, life prediction methods have become increasingly relevant. This led to the development of formulas describing the relationship between strain and the number of repeated cycles. For the low-cycle fatigue, Manson (1953) and Coffin (1954) proposed what is now widely known as the Coffin-Manson relation.

The understanding of the role of the crack propagation stage spurred the development of fracture mechanics. This introduced a new quantitative parameter, the stress intensity factor, and its associated formula, both of which play a key role in predicting crack propagation rates. The Damage Tolerance concept, widely accepted in modern aviation, is based on contemporary methods of fracture mechanics.

All these ways to predict the critical state of metal structures rely on empirical data regarding fatigue damage accumulation, as the most reliable and in-demand way to achieve practical results nowadays (Westmoreland Mechanical Testing & Research Inc., n.d.). Empirical data collection provides predictions of the average or probabilistic values of fatigue life, while predicting the remaining life of particular structure requires individual fatigue damage monitoring. This requirement is confirmed by the significant scatter of fatigue lives, as described by the Normal or Gaussian distribution and the Weibull distribution (Schijve, 2005). The most complicated situation arises with the irregular cyclical loading. To assess accumulated fatigue damage, Palmgren-Miner's rule is generally accepted (Palmgren, 1924; Miner, 1945), but the accuracy of the method doesn't always meet expectations.

Fatigue process consists of two main stages: nucleation of cracks, and crack propagation. The duration of these stages can vary, but neither stage can be ignored in the assessment of total fatigue life. This paper considers the efforts aimed at assessing fatigue damage accumulated during the initial phase of fatigue using fatigue indicators based on the quantitative analysis of surface deformation relief (surface pattern) formed by extrusions, intrusions, and persistent slip bands. The application of these fatigue indicators addresses the problem of fatigue lives scatter by using an individual approach to the fatigue analysis of specific structures.

The papers focus on two types of engineering designs: a) aircraft, and b) steel bridges. Analysis of accidents, non-destructive inspections, and Structural Health Monitoring reveal that fatigue is crucial problem for both categories of structures. Information related to accidents in aviation has been accumulated in Aviation Safety Database (Aviation Safety Network, 2020), presented in the work of U. Goranson (Goranson, 1998). Case studies for bridges fatigue failure are described in the works (Leonetti et al., 2024) and Samim et al. (2023).

There are different methods of measuring accumulated fatigue damage. A comprehensive review of contemporary methods for metal fatigue diagnostics can be found in the review of fatigue damage detection and measurement techniques (Bjørheim et al., 2022). Despite the development of increasingly sophisticated methods, no single method is versatile. Each method is suited to specific materials, loading conditions, design, etc.

Some of these prospective methods could potentially be integrated with the Fatigue Indicators for Metal Structures (FIMS) described below, offering enhanced data on accumulated damage. These are: a) electrical resistance monitoring (Nobile & Saponaro, 2021; Eifler et al., 2016), micro hardness measurements (Drumond et al., 2017), the X-ray diffraction (XRD) method (Pangborn & Zamrik, 1991; Zhan et al., 2021), and others. These methods are able to respond changes in the Fatigue Indicator, attached to the monitored structure.

The change in electrical resistance is associated with both stages of the fatigue process: (a) the increase in dislocation density, leading to damage accumulation and the nucleation of fatigue cracks, and (b) the propagation of fatigue cracks. The proposed FIMS relies on the detection and monitoring of surface intrusions and extrusions, which share the same dislocation-based nature. This makes the two methods complementary and suitable for integration.

Microhardness measurements are included here due to their high sensitivity. This method effectively reflects the staged nature of metal fatigue and can inspect localized areas of plastic deformation, such as extrusions and intrusions, which serve as key indicators in FIMS.

X-ray diffraction (XRD) method has been affective both for evaluation of the accumulated fatigue damage and prediction of remaining life at high cycle fatigue and low cycle fatigue. In the work (Zhan et al., 2021) aluminium alloy 2024 was studied. The dislocation density of the fatigue loading was found, thus method is sensitive to the micro processes at the fatigue and also can be used for the further research and development of FIMS, wich is based on the possibility to monitor surface pattern caused by the dislocations motion.

This paper briefly describes the evolution of Fatigue Indicators for Metal Structures (FIMS), proposed and developed with participation of the authors of this paper in different years and according to the different projects, from the initial concept to a family of indicators capable of monitoring the fatigue damage of key structural elements in aircraft made from aluminum alloys and bearing elements in steel bridges. In all discussed indicators, the key parameter of accumulated fatigue damage is the intensity of the surface deformation relief as assessed by the computer-aided optical method. The described approach can also be referred to as the method of witness samples, because it relies on the application of samples working in the same conditions as the inspected structure.

2. Concept of the method for metal fatigue monitoring by surface deformation relief

The Single-Crystal fatigue indicator (Zasimchuk et al., 1992). was both the first and a conceptual approach for the assessment of accumulated fatigue damage through so-called "Deformation relief" produced by cyclical loading. The first structurally sensitive fatigue indicator was made from a single-crystal aluminium foil (99.99% Al) with crystallographic orientation <221> {110}. Indicators were glued to the structural elements of aircraft.

Slip lines have been considered indicators of fatigue damage. As the number of applied cycles increases, the density of slip lines also increases, making it possible to predict residual life based on slip lines density.

An additional potential of the single crystal sensor arises from the observed initiation and progression of the slip process in additional slip systems. These slip lines form in a different direction but are also influenced by the stress level, thereby enabling the monitoring of static overloading.

The idea has further developed with the application of fractal geometry, for example, in the work of Gordienko et al. (1995). The search for practical applications of "surface relief as a fatigue indicator" has led to the study of surface processes on construction materials. Clad aluminium alloys were studied using a complex of methods: light microscopy as a primary method, as well as scanning microscopy, transmission microscopy, profiler, etc.

3. Surface relief of clad aluminium alloys

For manufacturing aircraft skin, the alclad aluminium alloys 2024-T3, 7075-T6, and some new materials are used. The main alloying components of 2024-T3 are copper and magnesium, while 7075-T6 contains about 5% of zinc. To reduce the possible corrosion process, sheets are covered with a layer of pure aluminium (for 2024-T3) or with a layer of aluminum with 1.0% Zn (for 7075-T6). The thickness of the clad layer ranges from 4 to 7% of the total sheet thickness. The 2024-T3 alloy composition is presented in Table 1 (ASM Aerospace Specification Metals Inc., n.d.). Table 2 represents the mechanical properties of the alloy (ASM Aerospace Specification Metals Inc., n.d.).

Table 1. 2024-T3 chemical composition

Al, wt.%	Cu, wt.%	Mg, wt.%	Mn, wt.%	Si, wt.%	Fe, wt.%	Zn, wt.%	Ti, wt.%	Other, wt.%
90.7–94.7	3.8–4.9	1.2–1.8	0.3–0.9	Max 0.5	Max 0.5	Max 0.5	Max 0.15	Max 0.15

Table 2. 2024-T3 mechanical properties

Ultimate Tensile Strength, MPa	Yield Stress, MPa	Elongation at Break, %	Modulus of Elasticity, GPa	Shear Strength, MPa
483	345	18	73.1	283

Aluminium alloy Alclad 2024-T3 has similarities to the following standard designations and specifications as sheet: Alclad 2024-T3, AMS 4041, AMS QQ-A-250/5, AIR 9048-140, ASTM B209, BSL 109, WS 3.1364, EN 2090 (Reference metal).

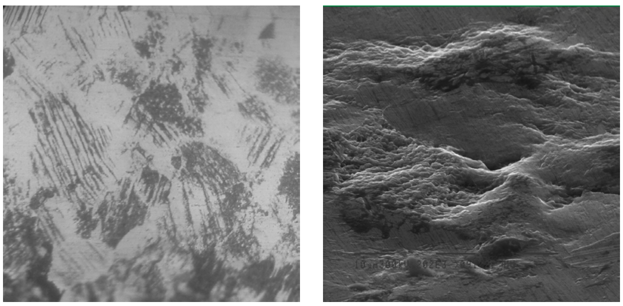
For polycrystalline metals as well as for single-crystals, the cyclic loading above a certain level leads to the development of extrusion/intrusion structures (Figure 1). The intensity of the relief formed by the extrusion/intrusion structure intensity depends on the stress level, the distribution of stress near the stress concentrator, and the number of cycles (Karuskevich et al., 2012). For the quantitative assessment of accumulated fatigue damage, the computer-aided optical method was proposed based on the analysis of the intensity of the extrusion/intrusion structure.

Due to the need to determine the effect of the loading sign on the formation and evolution of the deformation relief, an electron microscopic study was also conducted. A sample was examined after 250,000 cycles of cantilever bending. The stress in the surface layer in the research area was 173.2 MPa.

The electron microscopic study did not reveal any qualitative or quantitative differences in the relief structures formed as a result of compressive and tensile stresses.

As a result of the measurements of the extrusion and intrusion dimensions, the data obtained are presented in Table 3.

The correlation between the intensity of deformation relief and the number of cycles to failure was found under different loading modes (Figure 2). As a quantitative parameter for deformation relief and corresponding fatigue damage, the parameter of relief intensity, *D*, was proposed. It is calculated as the ratio of the surface with signs of relief to the total area of the investigated spot.



a) b)

Figure 1. Extrusion/intrusion structure on the surface of the cladding layer after 120,000 cycles at a stress of σ = 150 MPa; *R* = 0: a – light microscopy; b – scanning microscopy

Table 3. Dimensions of the extrusions and intrusions under compression and tension

Height of the extrusions at tension, h_e^p	Height of the extrusions at at compression, h_e^c	Depth of the intrusions at tension, h_i^p	Depth of the intrusions at compression, h_i^c
~1.3...4.5 μm	~1.3...4.7 μm	~ 1.6...3.2 μm	~ 1.3...3.8 μm

Results of fatigue monitoring are shown in Figure 2.

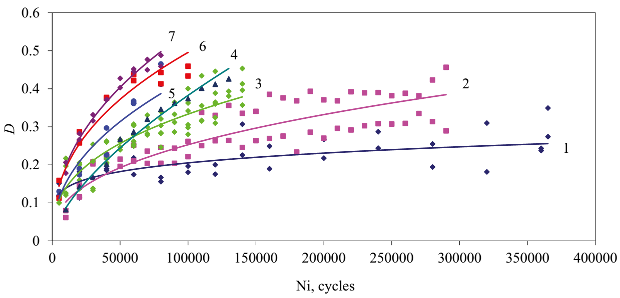


Figure 2. Evolution of the surface deformation relief in the process of cyclical loading: 1 – σ_{max} = 76.9 MPa; 2 – σ_{ma}= 81.7 MPa; 3 – σ_{ma}= 96.2 MPa; 4 – σ_{ma} = 105.8 MPa; 5 – σ_{ma} = 115.4 MPa; 6 – σ_{ma} = 129.8 MPa; 7 – σ_{ma} = 134.6 MPa

4. Polycrystalline fatigue indicators for aircraft

As a result of the surface relief study and due to the need for aircraft fatigue monitoring, the structurally sensitive FIMS (Figure 3) were proposed (Ignatovich et al., 2013).

The uniaxial FIMS resembles a small specimen designed for fatigue testing (Figure 3a). Its narrowed central section amplifies strain and stress locally, enabling it to reflect operational loading conditions through the formation of surface deformation relief. The distance between attachment points is designed to match the spacing of the structure's attachment elements, ensuring a non-invasive integration into the system.

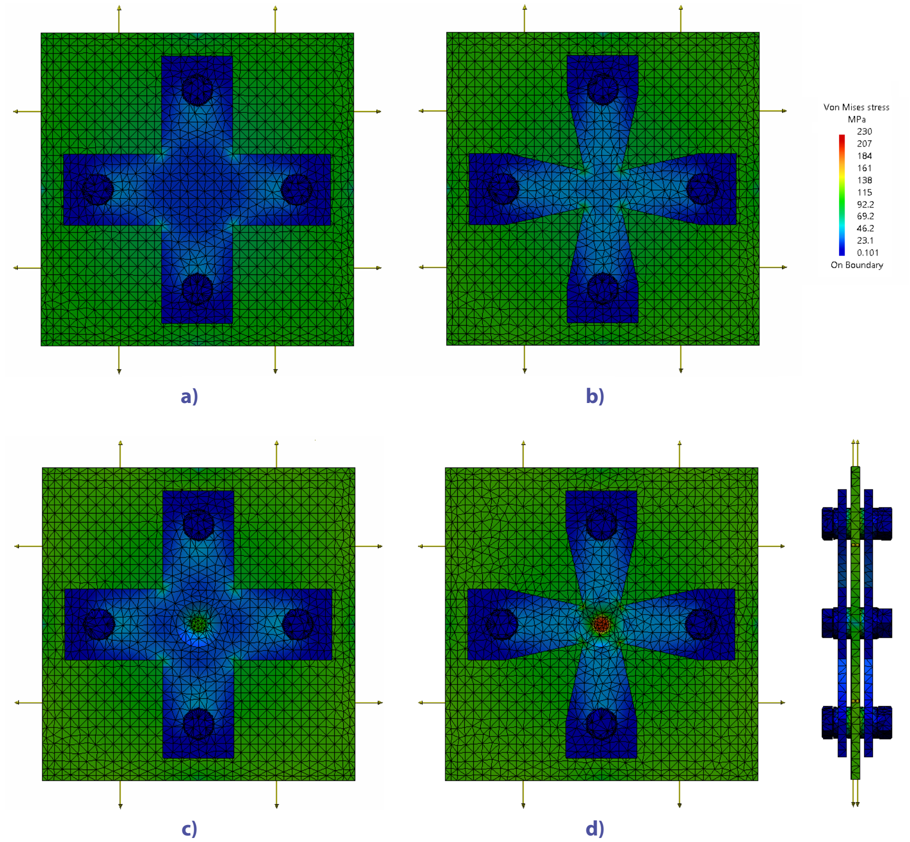


Figure 3. Evolution of biaxial fatigue indicator design: a) basic design without a stress concentrator in the central part; b) design with tapered arms; c) indicator featuring a hole as a stress concentrator; d – indicator with a sensitive element located in the center part

The FIMS geometry is optimized using Finite Element Analysis to enhance performance. For laboratory experiments, the working surface of the indicator is polished with diamond paste to facilitate optical observation of surface relief evolution. In mass production, electrogalvanic polishing can be employed for efficient surface finishing.

A fatigue indicator, made from the studied early alloy with a layer of pure plastic aluminium, undergoes cyclical loading that results in the formation of extrusions, intrusions, and persistence slip bands – indicative of accumulated fatigue damage. This surface structure has been quantitatively described using the damage parameter *D* and the fractal dimensions of deformation relief clusters *Dp/s*. A strong correlation between these parameters and the number of cycles has been identified. The installation of the fatigue indicator in the root section of the wing provides integral information regarding the history of loading and the corresponding accumulated fatigue damage (Karuskevich et al., 2022). Fatigue tests conducted under loading regimes similar to those encountered by planes in service have confirmed the ability to monitor fatigue damage in aircraft bearing components.

Analysis of aircraft loading leads to the understanding of the necessity and possibility of biaxial fatigue monitoring, using fatigue indicators (Karuskevich et al., 2024). This concept recently has been proposed. The search for the optimum design has gone through the evolution of its shape and geometry. Some steps of this process are shown in Figure 3.

5. Fatigue indicator for steel bridges

There are more than 1,234 kilometers of road bridges over 100 meters in the Europe (Gkoumas et al., 2019). Steel bridges accounted around 33%. This proportion is similar all over the world.

In Europe requirements to the bridges meet the Standard EN 1993 (Eurocode 3) (The European Union, 2006). Standard states that fatigue assessment should be carried out for all critical areas. Fatigue assessment is not applicable to: pedestrian bridges, bridges carrying canals or other bridges that are predominantly statically loaded, unless such bridges or parts of them are likely to be excited by wind loads or pedestrians; parts of railway or road bridges that are neither stressed by traffic loads nor likely to be excited by wind loads.

United States over the 617,000 bridges, about 42% of those bridges are at least 50 years old, and 7.5% of them are considered structurally deficient. Fatigue and fracture as main problems stand dawn only to the corrosion and influence structural integrity very much crucial problem.

In the US the primary standard for the steel bridges fatigue analysis is issued by American Association of State Highway and Transportation (American Association of State Highway and Transportation Officials, 2024). Among the points of the document there are Service Limit State, Fatigue and Fracture Limit State, Strength Limit State, and others, emphasizing the problem of metal fatigue.

The comprehensive analysis of the methods for steel bridges nondestructive inspection is presented in the paper (Dolati et al., 2021). NDI inspection for bridge begins from the visual testing, includes dye penetrant testing and magnetic particle testing, eddy current method, ultrasonic testing, acoustic emission testing, infrared thermography testing, radiographic testing. laser testing method. It should be noted that almost all these methods have been used recently in aviation industry, thus have a prospect of the integration with FIMS.

The highway bridge is subjected to a wide range of loads. These include dead loads, live loads, dynamic loads, environmental loads, and special loads (breaking and collision forces) (Tabsh & Nowak, 1991). Dead loads are loads produced by the weight of all structural components, nonstructural attachments, wearing surfaces, and utilities. Live loads are loads caused by vehicle (trucks) in motion. Dynamic loads combine three major factors: bridge dynamics, vehicle dynamics, and road roughness. Environmental loads include wave loads, wind loads, ice loads, and earthquake loads.

In the work of R. Haghani (Haghani et al., 2012), the results of over 100 fatigue cases in steel bridges were presented. It was demonstrated that fatigue cracks predominantly occur at the connection of bearing components.

The components of steel bridges, ranked from the highest to the lowest number of failure cases, are as follows: Connections between floor beams and the main load-carrying members; diaphragms and cross-bracing connections; coped and cut-short beam ends; orthotropic decks; stringer-to-floor-beam connections; fatigue cracking from weld defects; additional stress component in members with change in section; secondary vibration-induced stresses in hangers; connections of wind bracing; connections of wind bracing; flange gusset plates; cover plates.

Example of the fatigue crack in the bridge structure is shown in Figure 4.

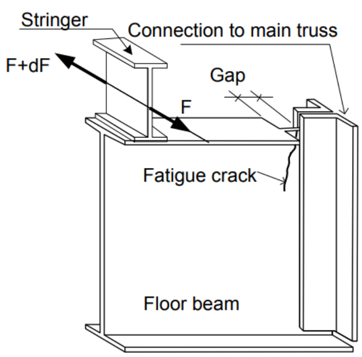


Figure 4. An example of a steel bridge component prone to fatigue (Haghani et al., 2012)

Several examples (SHM for Highway Bridges) reported to involve fatigue cracks in highway bridges. Distortion induced stresses have initiated cracks in the web-to flange welds and propagated into vertical cracks at the end of the web-to-connection plate welds (Integrated Structural Health Monitoring, n.d.); two cracks originated at the top of the web-to-stiffener weld were discovered on the webs of two steel girders (I-895 Bridge over U.S. Route 1 and the Patapsco River in Elkridge, Maryland), fatigue cracking induced damages to the eye-bars of the existing San Francisco Bay Bridge led to pieces of steel plummeting onto the roadway during rush hour.

Steel bridges fatigue is a crucial problem which comprises set of aspects: social (safety), economical (high cost of structures, impact on transportation system efficiency), engineering (improvement of design and manufacturing), scientific (study of metal fatigue nature).

Fatigue Tests is one of the most effective way to study the fatigue performance of steel bridges components, for example rib-to-deck welded joints (Fan et al., 2023). This paper describes results of the fatigue tests aimed to compare the fatigue performances of rib-to-deck welded joints under different welding processes. These models include single-sided welding specimens, double-sided partially penetrated welding specimens, and double-sided fully penetrated welding specimens. Each testing model consists of three crossbeams and four U-ribs, with the U-ribs and deck plates extending 500 mm from the center line of the crossbeams. However, the authors state that loading method is still different from the actual bridge load, thus the collection of the data regarding the behavior of the bridges components directly in the service, the monitoring of the loading and fatigue damage history should be considered as a mandatory procedure.

To prevent critical states due to metal fatigue, a complex set of information is collected by contemporary systems of Structural Health Monitoring (SHM). This refers to the strain, temperature, and displacement (Maulana et al., 2024). The data from these sensors are relevant to fatigue damage accumulation but do not provide direct information regarding the transformation of the metal microstructure, the level of accumulated fatigue damage, or the remaining life.

Elements of the steel bridges withstand irregular loads; thus, methods for calculating accumulated damage are in demand even when comprehensive data regarding strain, stress, and the number of cycles have been collected. The Palmgren-Miner rule is not able to provide correct data about accumulated fatigue damage, thus the proposed FIMS can be used to improve the estimation of fatigue life.

The proposal to adapt FIMS, originally developed for aircraft structures, to fatigue monitoring in steel bridges is grounded in a key feature of the FIMS concept: its surface relief reacts to repeated strain cycles, independent of the material properties of the inspected component. However, establishing an experimentally validated correlation between the accumulated fatigue damage of the inspected component and the surface relief pattern is essential. This correlation will be the focus of the next phase of research, which aims to broaden the application scope of FIMS.

Combining the autonomous structurally sensitive FIMSs with a network of strain gauges, accelerometers, and temperature sensors to monitor dynamic responses under various load conditions allows for establishing correlations between the loading history and fatigue damage accumulation. These correlations allow the application of a limited number of fatigue indicators for the machine learning of the existing Structural Health Monitoring system for bridges with an expanded network of wireless strain gauges and other relevant data sources. Fatigue damage monitoring is not only important for prevention unexpected failure but also for extending the load-carrying capacity and providing subsequent economic benefits.

Taking into account the successful experience of developing fatigue indicators for aviation structures, the first generation of indicators for steel bridges is currently under research and development. It was suggested to make new indicators from the same materials as proposed earlier, namely clad aluminium alloy 2024T3 having cladding layer made of pure aluminium 1050.

In the system "Steel bridge element" – "Core alloy of the indicator (2024T3)" – "Cladding layer of the indicator (pure aluminium 1050)," the strain of the bridge element is equal to the core of the indicator and the strain of the cladding layer. The characteristics of 2024T3 alloy are in Table 4, and characteristics of the 1050 aluminium are shown below (Table 5) (United Aluminum, n.d.).

Taking into account the expected lifespan of steel bridges, it seems evident to set operating stresses and stresses for tests below the endurance limit, but the selection of this stress level is questionable.

Traditional fatigue tests consider N = 10^7 cycles as an endurance limit. However, recent giga-cycle fatigue tests performed on a cold-rolled steel sheet (σ_{ult} = 340 MPa) and a high-carbon chromium steel (σ_{ult} = 2316 MPa) showed that the fatigue limit does not appear until 10^9 cycles in the S–N curve. Thus, the existence of an endurance limit is questionable at the moment and requires high-frequency fatigue tests (Bathias, 1999).

Among the steels used for the bridges design, S355 and S275 have been selected for consideration regarding the possibility of monitoring accumulated fatigue damage using FIMS. Steel S355 is predominantly used in highway bridge applications, as it provides the optimum balance between stiffness and strength. Steel S275 is often used in railway bridges, where stiffness rather than strength governs the design, or where fatigue is the critical design component (SteelConstruction).

The main chemical components of the steel selected for analysis are shown in Table 6. Mechanical characteristics of steels S275 and S355 are presented in Table 7 (Velling, 2019).

Table 4. Mechanical characteristics of aluminium 1050

Alloy-Temper	Tensile Strength, MPa	Yield Strength, MPa	Elongation, %
1050-0	75.8	27.57	40

Table 5. Chemical composition of 1050

Si	Fe	Cu	Mn	Mg	Zn	Ti	Others-Each	Others Total	Al Min
0.25	0.40	0.05	0.05	0.05	0.05	0.03	0.03	–	99.50

Table 6. Chemical content of steels S275 and S355

Composition	Steel S275	Steel S355
Manganese (Mn), max	1.6	1.6
Silicon (Si), max	0.05	0.05
Carbon (C), max	0.25	0.23
Phosphorus (P), max	0.04	0.05
Sulfur (S), max	0.05	0.05

Table 7. Mechanical characteristics of hot-rolled non-alloy structural steels

Parameter	S275	S355
Yield strength, MPa	255	410
Ultimate strength, MPa	410	550

The modulus of elasticity, *E*, used in the following calculations is accepted as 210 000 MPa (Eurocode Applied, 2017). The S275 endurance limit is accepted to be σ = 159 MPa (Aldeeb & Abduelmula, 2018), while the S355 endurance limit is σ = 260 MPa (Kucharczyk et al., 2012). According to the Hooke's law:

$\varepsilon = \sigma/E$,

where: σ – stress; *E* – modulus of elasticity; ε – strain.

From this: for steel S275, the strain corresponding to endurance limit is:

ε = 159 MPa /210000MPa = 0.0007571;

For steel S355, the strain correspondent to endurance limit is:

ε = 260 MPa /210000MPa = 0.001238.

The strain corresponding to the fractions of the endurance limit is shown in Table 7 and 8. The range of strain of practical interest has been defined based on the analysis presented in the work (Leonetti et al., 2024). As the extrusion/intrusion structure is a feature of microplastic deformation, the stress level in the cladding layer must be equal to or above the yield strength. For pure aluminium, linear elasticity is valid up to σ_{Lin} = 8 MPa (Wadee, 1999). The corresponding strain is calculated as:

$\varepsilon = \sigma / E_{al}$,

E_{al} – aluminium modulus of elasticity, E_{al} = 69 kN/mm^2 = 69000 MPa, ε = 8 MPa/69000 MPa = 1.15942e-4 = 0.000115942.

Table 8. Required coefficient of strain multiplication for steel S275 at different stress levels

Fraction of the Endurance Limit/ Stress, MPa	Strain of the structural element	Strain of the Indicator without effect of strain multiplication	Strain of the indicator required for relief nucleation and developed	Required coefficient of strain multiplication
1.0/159	0.007571	0.0007571	0.000115942	0.15313 – no need for the strain multiplication
0.5/79.5	0.00037855	0.00037855	0.000115942	0.30627 – no need for the strain multiplication
0.1/15.9	0.00007571	0.00007571	0.000115942	1.53139
0.05/7.95	0.000037855	0.000037855	0.000115942	3.06279

Table 9. Required coefficient of strain multiplication for steel S355 at different stress levels

Fraction of the Endurance Limit/ Stress, MPa	Strain of the structural element	Strain of the Indicator without effect of strain multiplication	Strain of the indicator required for relief nucleation and development	Required coefficient of strain multiplication
1.0/260	0.001238	0.001238	0.000115942	0.09365 – no need for the strain multiplication
0.5/130	0.000619	0.000619	0.000115942	0.18730 – no need for the strain multiplication
0.1/26	0.0001238	0.000123	0.000115942	0.94261 – no need for the strain multiplication
0.05/13	0.0000619	0.0000619	0.000115942	1.87305
0.01/2.6	0.00001238	0.00001238	0.000115942	9.36526

If the strain level of the indicator is insufficient for the formation of the deformation relief in the cladding layer, the required level can be achieved by optimizing the indicator's geometry. The coefficient of strain multiplication is calculated as the ratio of the strain in the narrow working site of the indicator to the strain in the widest site of the indicator. The results of the required coefficients of the strain multiplication for different loading conditions for the steel components of bridges are shown in Tables 8 and 9.

The results presented in the Tables 7 and 8 also show the strain conditions when the multiplication of stresses and strain is not required. When multiplication is required, it can be achieved by selecting the appropriate indicator's geometry.

6. Conclusions

This article explores two potential applications of the Fatigue Indicator for Metal Structures. Through extensive research, it was demonstrated that FIMS effectively monitors fatigue damage in aircraft components. Initially conceived as a foil-based single-crystal fatigue sensor, FIMS evolved into a polycrystalline variant capable of responding to both uniaxial and multiaxial cyclic loading.

The proposed method leverages the formation and development of extrusion/intrusion structures under repeated loads. This approach was first validated for aluminum alloy components in aircraft. The effectiveness of the fatigue indicators has been substantiated through mechanical testing, light and scanning electron microscopy, and a validated computer-aided analysis procedure under varying stress-strain conditions.

It is proposed to use FIMS's for fatigue monitoring in steel bridges. However, further experimental work is needed to validate this approach, particularly focusing on calibrating FIMS to establish the relationship between fatigue damage in the indicator and the structural element.

The paper also highlights the potential of low-cost, autonomous, wireless FIMS devices as precursors to extended non-destructive testing. These indicators can help prioritize inspection schedules for aircraft, bridges, or other structures subjected to cyclical loading.

FIMS devices should be mounted at critical structural points experiencing tensile stress to reflect the level of accumulated fatigue damage. Their placement can be determined through conventional finite element analysis.

Unlike strain gauges commonly used in Structural Health Monitoring systems to measure real-time strains and stresses, FIMS provides information about accumulated fatigue damage. This capability allows it to correct errors associated with Miner's rule, offering a more reliable assessment of structural fatigue.

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Author contributions

M. Karuskevych developed the key principles of a new approach for monitoring metal fatigue, T. Maslak conducted the fatigue experiments and data interpretation, O. Karuskevych was responsible for the study of steel bridges loading analysis, Yu. Vlasenko performed FEA of the fatigue indicators.

Disclosure statement

The authors declare that they do not have any competing financial, professional, or personal interests from other parties.

References

American Association of State Highway and Transportation Officials. (2024). *AASHTO LRFD bridge design specifications* (10th ed.). AASHTO.

Aldeeb, T., & Abduelmula, M. A. (2018). Fatigue strength of S275 mild steel under cyclic loading. *World Academy of Science, Engineering and Technology International Journal of Materials and Metallurgical Engineering*, *12*(10), 564–570.

ASM Aerospace Specification Metals Inc. (n.d.). *2024-T3 aluminum alloy* [Data sheet]. Retrieved May 12, 2025, from http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma2024t3

Aviation Safety Network. (2020). *ASN aviation safety database*. https://aviationsafety.net/database/

Bathias, C. (1999). There is no infinite fatigue life in metallic materials. *Fatigue & Fracture of Engineering Materials & Structures*, *22*(7), 559–565. https://doi.org/10.1046/j.1460-2695.1999.00183.x

Bjørheim, F., Siriwardane, S. C., & Pavlou, D. (2022). A review of fatigue damage detection and measurement techniques. *International Journal of Fatigue*, *154*, Article 106556. https://doi.org/10.1016/j.ijfatigue.2021.106556

Coffin, L. F. (1954). A study of the effects of cyclic thermal stresses on a ductile metal. *Transactions of the American Society of Mechanical Engineers*, *76*(6), 931–950. https://doi.org/10.1115/1.4015020

Dolati, S., Caluk, N., & Mehrabi, A. (2021). Non-destructive testing applications for steel bridges. *Applied Sciences*, *11*(20), Article 9757. https://doi.org/10.3390/app11209757

Drumond, G., Roudet, F., Pasqualino, I., Pinheiro, B., Chicot, D., & Decoopman, X. (2017, August 28–September 1). High-cycle fatigue damage evaluation of steel pipelines based on microhardness changes during cyclic loads. In *Proceedings of the 23rd Congrès Français de Mécanique* (pp. 1–8). Université de Lille. https://doi.org/10.1115/OMAE2017-62677

Eifler, D., Smaga, M., & Klein, M. (2016). Fatigue monitoring of metals based on mechanical hysteresis, electromagnetic ultrasonic, electrical resistance and temperature measurements. *Mechanical Engineering Journal*, *3*(6), Article 16–00303. https://doi.org/10.1299/mej.16-00303

Eurocode Applied. (2017, October 9). *Eurocode 3 – table of design material properties for structural steel*. https://eurocodeapplied.com/design/en1993/steel-design-properties

Fan, C., Da, L., Wang, K., Song, S., & Chen, H. (2023). Fatigue tests and failure mechanism of rib-to-deck welded joints in steel bridges. *Sustainability*, *15*(3), Article 2108. https://doi.org/10.3390/su15032108

Goranson, U. G. (1998). Fatigue issues in aircraft maintenance and repairs. *International Journal of Fatigue*, *20*(6), 413–431. https://doi.org/10.1016/S0142-1123(97)00029-7

Gordienko, G., Zasimchuk, E., & Karuskevich, M. (1995). Forecasting the critical state of a deformed crystal by analysis of smart defect structure: Fractal characteristics and percolation critical indexes. In *Sensors and their Applications VII* (pp. 387–392). Institute of Physics Publishing.

Gkoumas, K., Marques dos Santos, F. L., van Balen, M., Tsakalidis, A., Ortega Hortelano, A., Grosso, M., Haq, G., & Pekár, F. (2019). *Research and innovation in bridge maintenance, inspection and monitoring – A European perspective based on TRIMIS* (EUR 29650 EN). Publications Office of the European Union. https://doi.org/10.2760/719505

Haghani, R., Al-Emrani, M., & Heshmati, M. (2012). Fatigue-prone details in steel bridges. *Buildings*, *2*(4), 456–476. https://doi.org/10.3390/buildings2040456

Ignatovich, S. R., Menou, A., Karuskevich, M. V., & Maruschak, P. O. (2013). Fatigue damage and sensor development for aircraft structural health monitoring. *Theoretical and Applied Fracture Mechanics*, *65*, 23–27. https://doi.org/10.1016/j.tafmec.2013.05.004

Integrated Structural Health Monitoring. (n.d.). *Development of self-sustained wireless integrated structural health systems for highway bridges*. Intelligent Structural Health Monitoring Laboratory, University of Maryland. Retrieved May 12, 2025, from http://ishm.umd.edu/about/background.html

Karuskevich, M., Karuskevich, O., Maslak, T., & Schepak, S. (2012). Extrusion/intrusion structures as quantitative indicators of accumulated fatigue damage. *International Journal of Fatigue*, *39*, 116–121. https://doi.org/10.1016/j.ijfatigue.2011.02.007

Karuskevich, M., Maslak, T., Gavrylov, I., Pejkowski, Ł., & Seyda, J. (2022). Structural health monitoring for light aircraft. *Procedia Structural Integrity*, *36*, 92–99. https://doi.org/10.1016/j.prostr.2022.01.008

Karuskevich, M., Maslak, T., Vlasenko, Y., & Pejkowski, Ł. (2024). Biaxial fatigue indicator. *Procedia Structural Integrity*, *59*, 642–649. https://doi.org/10.1016/j.prostr.2024.04.091

Kucharczyk, P., Rizos, A., Münstermann, S., & Bleck, W. (2012). Estimation of the endurance fatigue limit for structural steel in load-increasing tests at low temperature. *Fatigue & Fracture of Engineering Materials & Structures*, *35*(7), 628–637. https://doi.org/10.1111/j.1460-2695.2011.01656.x

Leonetti, D., Kinoshita, K., Takai, Y., & Nussbaumer, A. (2024). Fatigue behavior of transverse attachments under constant and variable amplitude loading from a Swiss motorway bridge. *International Journal of Fatigue*, *178*, Article 108003. https://doi.org/10.1016/j.ijfatigue.2023.108003

Manson, S. S. (1953). *Behavior of materials under conditions of thermal stress* (NASA Technical Note, 2933). NASA.

Miner, M. A. (1945). Cumulative damage in fatigue. *Journal of Applied Mechanics*, *12*(3), A159–A164. https://doi.org/10.1115/1.4009458

Maulana, Y., Wibowo, E., & Marlina, L. (2024). Optimization of structural health monitoring for steel bridges using wireless sensor networks and machine-learning algorithms. *International Journal of Mechanical, Electrical and Civil Engineering*, *1*(2), 11–16. https://doi.org/10.61132/ijmecie.v1i2.65

Nobile, R., & Saponaro, A. (2021). Real-time monitoring of fatigue damage by electrical resistance change method. *International Journal of Fatigue*, *151*, Article 106404. https://doi.org/10.1016/j.ijfatigue.2021.106404

Pangborn, R. N., & Zamrik, S. Y. (1991). Fatigue damage assessment by X-ray diffraction and nondestructive life-assessment methodology. In C. O. Ruud, J. F. Bussière, & R. E. Green (Eds.), *Nondestructive characterization of materials IV* (pp. 351–362). Springer. https://doi.org/10.1007/978-1-4899-0670-0_31

Palmgren, A. (1924). The service life of ball bearings. *Process Engineering*, *68*, 339–341.

Reference Metal. (n.d.). *Company profile*. Retrieved May 12, 2025, from https://www.referansmetal.com/hakkimizda.php

Samim, M., Sekiya, H., & Hirano, S. (2023). Evaluation of fatigue damage in steel girder bridges using displacement influence lines. *Structures*, *53*, 1160–1171. https://doi.org/10.1016/j.istruc.2023.04.126

Schijve, J. (2005). Statistical distribution functions and fatigue of structures. *International Journal of Fatigue*, *27*(9), 1031–1039. https://doi.org/10.1016/j.ijfatigue.2005.03.001

SteelConstruction.info. (n.d.). *Bridges*. Retrieved May 12, 2025, from https://steelconstruction.info/Bridges

Tabsh, S. W., & Nowak, A. S. (1991). Reliability of highway girder bridges. *Journal of Structural Engineering*, *117*(8), 2372–2388. https://doi.org/10.1061/(ASCE)0733-9445(1991)117:8(2372)

The European Union. (2006). *Eurocode 3: Design of steel structures – Part 2: Steel bridges* (EN 1993-2). European Committee for Standardization.

United Aluminum. (n.d.). *1050 aluminum alloy* [Technical data]. Retrieved May 12, 2025, from https://unitedaluminum.com/1050-aluminum-alloy/

Velling, A. (2019, 7 January). Structural steels S235, S275, S355, S420 and their properties. *Fractory Blog*. https://fractory.com/structural-steels-s235-s275-s355-s420-and-their-properties/

Wadee, M. A. (1999). Experimental evaluation of interactive buckle localization in compression sandwich panels. *Journal of Sandwich Structures & Materials*, *1*(3), 230–254. https://doi.org/10.1177/109963629900100304

Westmoreland Mechanical Testing & Research Inc. (n.d.). *History of fatigue testing*. Retrieved May 12, 2025, from https://www.wmtr.com/History_Of_Fatigue_Testing.html

Zasimchuk, E. E., Radchenko, A. I., & Karuskevich, M. V. (1992). Single-crystals as an indicator of fatigue damage. *Fatigue & Fracture of Engineering Materials & Structures*, *15*(12), 1281–1283. https://doi.org/10.1111/j.1460-2695.1992.tb01263.x

Zhan, J., Zhang, G., Ma, J. F., Liu, Z., & Song, J. (2021). Determination of the resonance fatigue dislocation density of a 2024 aluminum alloy by X-ray diffraction. *Strength of Materials*, *53*(2), 239–247. https://doi.org/10.1007/s11223-021-00323-w