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Original scientific paper

FAILURE MODE AND EFFECT ANALYSIS-BASED RISK ASSESSMENT OF A BRIDGE CRANE MAIN GIRDER

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A b s t r a c t: This paper presents an integrated approach for evaluating the condition and failure risks of the main girder in a bridge crane. The study uses numerical simulations performed in Ansys. The critical stress zones for various trolley positions and dynamically amplified loads are identified using numerical analyses. In the following phase, the results from the numerical analysis are used as input for the Failure Mode and Effect Analysis - FMEA method. Based on the generated FMEA, the data are further utilized to develop a MATLAB algorithm that integrates the FMEA parameters and provides an assessment of the structural condition and failure risks. The suggested methodology enables an improved approach to crane inspection and maintenance planning.

Key words: bridge cranes; main girder; FMEA

ПРОЦЕНА НА РИЗИК ЗАСНОВАНА НА АНАЛИЗАТА НА МОЖНИ НЕИСПРАВНОСТИ И ПОСЛЕДИЦИ НА ГЛАВНИОТ НОСАЧ НА МОСТОВСКА ДИГАЛКА

А п с т р а к т: Овој труд претставува интегриран пристап за оценување на состојбата и ризиците од отказ на главниот носач кај мостовска дигалка. Преку нумеричките анализи во Ansys се идентификувани критичните зони на напрегања за различни положби на количката, како и при динамички зголемени оптоварувања. Во следната фаза, резултатите од нумеричката анализа се користат како влезни податоци за методот Анализа на можните неисправности и последици (анг. *FMEA*). Добиената *FMEA* се имплементира во алгоритамот *MATLAB* кој ги интегрира параметрите на *FMEA* и овозможува процена на структурната состојба и ризиците од отказ. Предложената методологија овозможува подобрен пристап кон инспекцијата и планирањето на одржувањето на дигалките.

Клучни зборови: мостовски дигалки; главен носач; анализа на можни неисправности и последици

1. INTRODUCTION

One of the most important and critical elements in the construction of bridge cranes is the main girder, therefore, its condition largely determines the safety of crane operation [1, 2]. The need for such research is supported by a review of earlier studies in the fields of crane engineering, reliability assessment, maintenance, and crane inspection [3, 4, 5, 6]. The research [7] focuses on safety regulations, identifying inconsistencies within national standards and suggesting more precise and unified guidelines to reduce crane-related accidents. In [8], traditional FMEA is enhanced with multicriteria decision-making tools to better assess failure modes in renewable energy systems, while [9] examines the impact of human factors, such as noise and mental exhaustion, using a virtual reality crane simulator. Industry 4.0 applications are addressed in [10], where machine-vision methods in conjunction with PFMEA and DFMEA enhance production quality control. Studies [11] and [12] examine real operational issues in crawler cranes and crane guiding structures, using experimental data and FMEA to identify causes of failures and excessive wear. Methodological developments of FMEA appear in [13], which introduces Z-numbers and clustering algorithms, and in [14], where fault trees, Bayesian networks, and Markov chains are integrated to evaluate crane reliability. Broader safety factors in construction environments are explored in [15]. Risk-assessment improvements are further presented in [16] using Z-numbers and set-pair analysis, and in [17], where human error risks are prioritised through cumulative prospect theory. Lastly, [18] combines Fishbone, Pareto, and FMEA analyses to identify dominant failure causes in crawler cranes, showing mechanical issues to be the most important. Overall, the literature indicates a shift towards integrated analytical models, sophisticated monitoring technologies, and stronger emphasis on human and operational factors to increase crane reliability and safety. Based on the conducted research, it is evident that accurately assessing the condition of the main girder requires a combined approach involving analytical calculations and modern numerical methods. As a result, the primary objective of this study is to identify the most critical parameters during crane operation. The focus of this research was to collect data and develop an algorithm for assessing the most critical element of the main girder. By generating and implementing a MATLAB code, this study aims to effectively support both crane inspection and maintenance. This research paper helps solve current and important challenges in scientific and professional studies related to crane maintenance and inspection.

2. METHODOLOGY

The methodological approach in this paper is based on applying earlier obtained analytical and numerical results into the FMEA method and implementing the outcomes in MATLAB. The analytical and numerical results used in this study originate from the author's unpublished structural analyses of the crane girder. These results were obtained as part of a broader research effort and are solely used here as structural indicators for identifying critical regions and supporting the FMEA procedure. The phases of the research are presented in Figure 1.

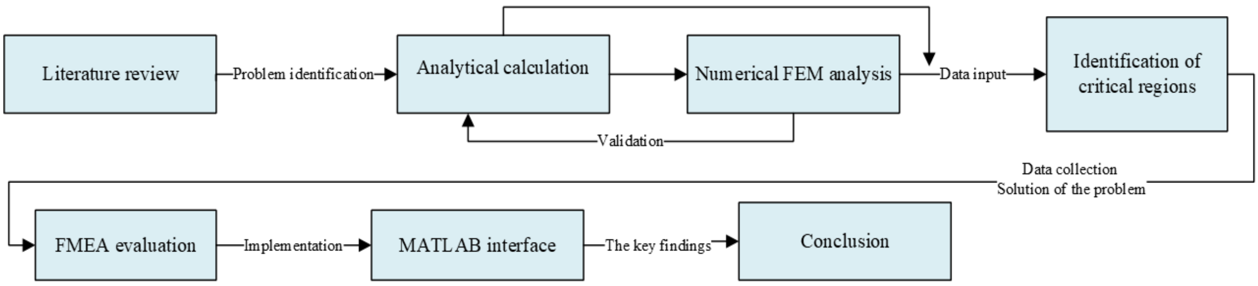


Fig. 1. Research methodology

3. STRUCTURAL ASSESSMENT RESULTS OF THE MAIN GIRDER

The main girder examined in this study belongs to a real bridge crane located at Institute of Earthquake Engineering and Engineering Seismology - IZIIS. A CAD model of the crane created in SolidWorks is shown in Figure 2.

a) *Analytical analysis of the main girder*

First, the main girder was calculated analytically. The main girder of the bridge crane is a welded box profile, whose geometry and material properties are derived from the crane documentation (Table 1) [19]. The analytical analysis is performed according to the classical beam theory, where the girder is modelled as a simply supported beam subjected to a uniformly distributed load q and a concentrated load Q with two variable positions, depending on the trolley location: at mid-span (L/2) and in an end position (e) [1, 2, 3]. The results indicates that the girder operates in the elastic range under the applied loading. The analytical results serve as a basis for verification with numerical analysis.

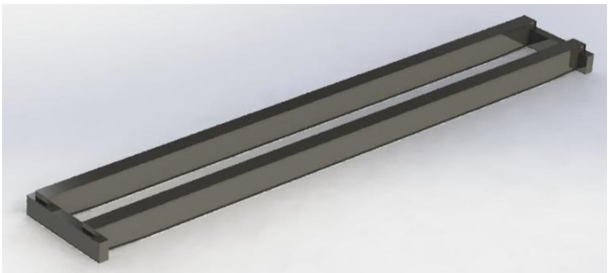


Fig. 2. CAD model of the main girder

Table 1

Geometrical characteristics and exploitation parameters of the main girder

	Characteristics / Parameters	Symbol	Value
	Height of the girder	H	700 mm
	Width of the girder	B	450 mm
	Thickness of top/bottom plate	T	8 mm
	Thickness of side plates	S1, S2	6 mm
	Moment of inertia	Ix	145284 cm^4
	Section modulus	Wy	1513 cm^3
	Lifting capacity	Q	10 t
	Span	L	16.24 m
	Lifting height	H	9 m
	Wheelbase of the trolley	LM	1450 mm
	Number of trolley wheels	–	4, divided 2 per side
	Driving class coefficient	γ	1.05
	Dynamic coefficient (for speed up to 15 m/min)	ψ	1.15
	Bridge acceleration coefficient	ka	0.15
	Trolley acceleration coefficient	Kam	0.15
	Skewing coefficient	λ	0.17
	Material		S235JR
Material parameters	Elastic modulus	E	2.10 × 10^{11} Pa
	Poisson’s ratio	ν	0.30
	Density	ρ	7850 kg/m^3
	Yield strength	fy	235 MPa
	Stress$_{allow}$	σ_{allow}	≈ 0.6·fy = 141 MPa

b) *Numerical analysis of the main girder*

The CAD model created in SolidWorks was transferred into ANSYS Workbench [21, 22], and discretized using higher-order quadratic three-dimensional solid elements (SOLID186). The girder is modelled in the numerical simulation as a simply supported beam, with one end vertically fixed and the other axially movable. Cases with the load at mid-span and in the end position were analysed, under nominal and dynamically increased loading (ψ = 1.05; 1.10 and 1.15) [14]. The adopted dynamic coefficients reflect the dynamic effects of load lifting and trolley motion under normal operating conditions. The mesh is denser in the areas where stress concentration is expected, around the supports and the trolley path, as well as coarser in the remaining parts. The model contains 98,786 nodes and 46,504 elements (Figure 3). A mesh density check was performed, where further refinement did not produce stress variations greater than σ < 3%. This confirms that the selected mesh is appropriate. Table 2 shows the stresses and deformations obtained from the static simulations in Ansys.

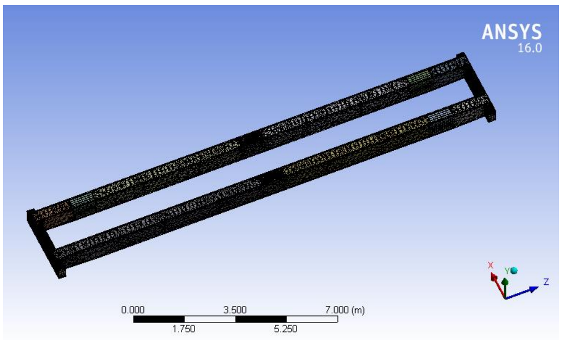


Fig. 3. Mesh

Table 2

Results of the static analysis: stresses and deformations

Case No.	Position of the trolley	Dynamic coefficient	Max stress	Max deformation
1	In the middle	1	155.59 MPa	4.42 mm
2	In the end position	1	117.98 MPa	2.29 mm
3	In the middle	1.05	160.48 MPa	4.57 mm
4	In the end position	1.05	114.34 MPa	2.287 mm
5	In the middle	1.10	180.04 MPa	8.22 mm
6	In the end position	1.10	119.34 MPa	2.36 mm
7	In the middle	1.15	282.73 MPa	8.22 mm
8	In the end position	1.15	125.12 MPa	2.44 mm

4. FAILURE MODE AND EFFECT ANALYSIS – FMEA

The FMEA method is presented in a table [21, 22]. Table 3 contains all elements that are necessary for identifying and evaluating the potential failures of the main girder of the bridge crane. The table is split into two sections, the first section being descriptive and including: identification of the components, the manner in which the component fails, and the main consequence of the failure. With ID, the numbering and decomposition of the potential failures are performed.

The failure mode clarifies how the failure might happen, i.e., what precisely may be the defect in each of the listed components. The following are listed as failure modes:

- *Local yielding at midspan.* – This failure mode is chosen because, based on the analytical and numerical analysis, the midspan is the location where the largest bending moment occurs, and therefore the highest stresses appear [23, 24, 25]. This failure mode is critical because any local yielding directly reduces the girder's ability to support load.
- *Stress concentration near end support.* – In the area of the end supports, according to the Ansys simulations it is noticeable that local high stresses appear, especially due to [26, 27]:

  – eccentric positioning of the trolley,

  – presence of welded joints and diaphragms.

  These effects create local concentrations which often indicate possible crack locations.
- *Excessive vertical deflection.* – Deformations are a key factor in the occurrence of failures. Excessive deformation may lead to [27, 28]:

  – difficulties in the movement of the trolley,

  – occurrence of vibrations,

  – increased fatigue of the structure.

  This mode is included because it does not necessarily cause a direct failure, but it critically affects functionality and safe operation. Results for the deformations that emerge are derived from the numerical simulations.
- *Effects of dynamic amplification*. – Cranes operate under real conditions where the load is never perfectly static. Accelerations, start/stop motions, micro-impacts and oscillations create a dynamic factor $\psi > 1$ [29]. The dynamic effects can significantly increase the stresses, as observed in the results from the numerical simulations.
- *Fatigue crack initiation.* – Bridge cranes operate with a large number of loading cycles. Repeated stresses, even if they are below the yield limit, can eventually initiate fatigue cracks, especially in areas with stress concentration (welds, diaphragms, end connections [30, 31]). Fatigue is one of the most common mechanisms of long-term failure in steel structures.

Main causes. – The factors or conditions that could lead to failure are listed, or the question of why that failure occurred is addressed.

- *High bending stress; dynamic load factor.* – As a cause for the occurrence of local yielding at midspan, it is the maximum bending moment that arises as well as the dynamic factors that additionally increase the stresses in that area [24, 25].
- *Eccentric trolley load; weld geometry*. – As a result of the different positions of the trolley, an uneven distribution of stresses appears. Stress

concentration may occur in areas where welds and geometric changes are present.

- *High service load; insufficient stiffness*. – Lifting larger loads and the structure's lack of stiffness may be the reasons for the main girder's deformations and tilt [28].
- *Sudden trolley movement; impact loads*. – Sudden accelerations, braking, and impact loads create short-duration but very high dynamic stresses. These conditions often lead to extreme structural responses [29].
- *Repeated load cycles; stress concentrations*. – This cause is typical for fatigue damage, because repeated loading cycles initiate cracks in areas with stress concentrations [30, 31].
- *Main consequences*. – This section lists the consequences that appear after the failure, i.e., how the failure affects the further operation and safety of the crane.
- *Loss of stiffness; local plasticity*. – This consequence is selected because local yielding directly leads to a reduction in stiffness and a decrease in the load-carrying capacity of the main girder [23, 24].
- *Local cracking; vibration issues*. – The stress concentration at the ends of the main girders most often results in local cracks and vibrations, which are common signs of early structural damage [26, 27].
- *Serviceability issues; trolley misalignment*. – Excessive deformation makes it difficult for the trolley to move, which directly interferes with safe operation [28].
- *Increased stresses; higher fatigue demand*. – The dynamic effects increase the stress C and accelerate fatigue damage, so this consequence is critical [29].
- *Crack growth; reduced load capacity*. – As loading cycles increase, fatigue-induced cracks grow, which reduces the load-carrying capacity of the entire girder and posesa serious risk of failure [30, 31].

Table 3

Failure mode and effect analysis – FMEA, of the main girder

ID	Failure mode	Main causes	Main effects	S	O	D	RPN
FM1	Local yielding at midspan	High bending stress; dynamic load factor	Loss of stiffness; local plasticity	9	4	4	144
FM2	Stress concentration near end support	Eccentric trolley load; weld geometry	Local cracking; vibration issues	8	4	5	160
FM3	Excessive vertical deflection	High service load; insufficient stiffness	Serviceability issues; trolley misalignment	7	4	3	84
FM4	Dynamic amplification effects	Sudden trolley movement; impact loads	Increased stresses; higher fatigue demand	8	3	6	144
FM5	Fatigue crack initiation	Repeated load cycles; stress concentrations	Crack growth; reduced load capacity	8	3	5	120

In addition to the descriptive assessment, the FMEA also includes a numerical evaluation of each failure mode in order to obtain a quantitative estimation of the risk. For each failure mode, three parameters are assigned: severity (S), occurrence (O), and detectability (D). These parameters are typically ranked on a scale of 1 to 10. Severity represents the consequences of the failure, occurrence reflects the expected frequency of the failure, while detectability evaluates how easily the failure can be identified during inspection. The Risk Priority Number (RPN) is calculated as (1) [32]:

$$RPN = S \cdot O \cdot D \tag{1}$$

A higher RPN indicates a more critical failure mode that requires greater attention, more frequent inspections, or preventive maintenance.

For the crane that is the subject of this study, the S (Severity) consequences if the failure occurs are determined according to:

- how seriously the damage affects safety,
- whether it significantly reduces the load-carrying capacity,

- whether it disrupts serviceability.

According to this,

- S = 9 means very severe consequences (local yielding, loss of stiffness),
- S = 7 means moderately severe consequences (large deformation),
- S = 8 means severe, but not critical consequences (stress concentrations, dynamic effects, fatigue).

The values for Occurrence (O) show how often the failure is expected to appear in real operation.

It is determined based on:

- number of loading cycles (fatigue),
- frequency of dynamic effects,
- trolley position.

So,

- O = 4, moderate likelihood (statically and geometrically induced stresses),
- O = 3, lower likelihood (dynamic effects, fatigue, which occur occasionally but not constantly, which is justified because the crane has been in operation for more than 40 years, implying a high number of accumulated loading cycles.

Detection (D) – the values for Detection show how easily the failure can be identified with common inspection methods. It is determined according to:

- visibility of the damage (plasticity, crack, large deformation),
- accessibility for inspection,
- need for NDT methods.

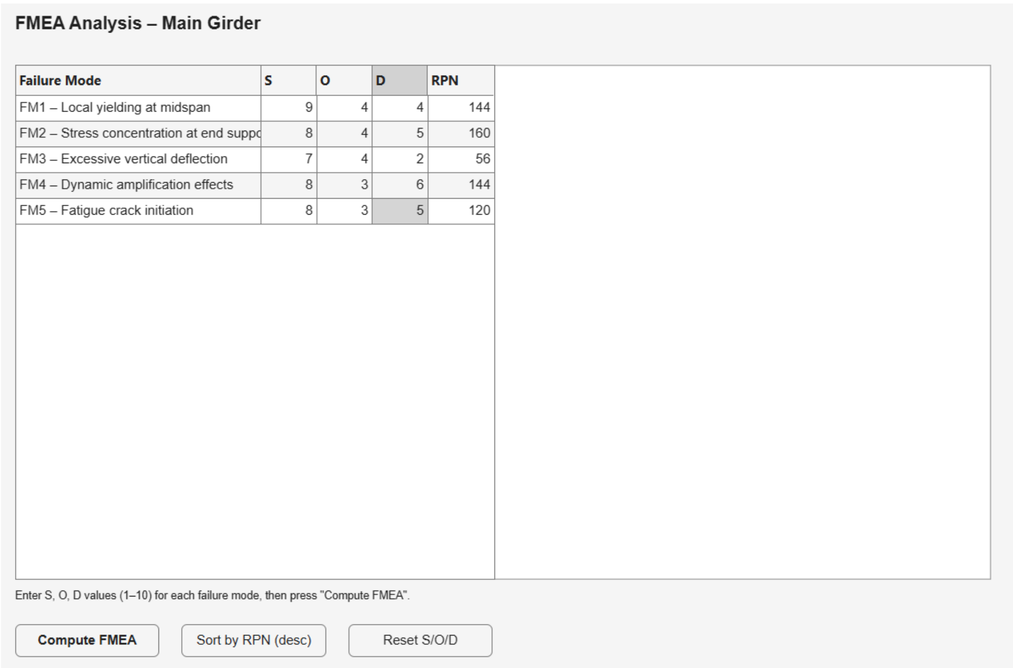
Specifically for this crane:

- D = 3–4 easily noticeable conditions (large deformation, plasticity),
- D = 5 harder to notice (stress concentrations, cracks around welded zones),
- D = 6 low detectability (dynamic effects that require measurement, not visually visible),

Through this approach, the FMEA serves as a link between the numerical analysis and the practical maintenance strategies, supporting informed decision-making aimed at improving reliability and safety during crane operation.

4.1. *Implementation of FMEA in MATLAB*

In the MATLAB implementation of the FMEA procedure, the user provides the three standard FMEA parameters for each identified failure mode: Severity (S), Occurrence (O), and Detection (D). These input values are assigned based on engineering judgement and on the structural indicators obtained from the numerical analyses, including maximum stresses, deformation levels, and the critical regions along the main girder (Figure 4).


FMEA Analysis – Main Girder

Failure Mode	S	O	D	RPN
FM1 – Local yielding at midspan	9	4	4	144
FM2 – Stress concentration at end suppo	8	4	5	160
FM3 – Excessive vertical deflection	7	4	2	56
FM4 – Dynamic amplification effects	8	3	6	144
FM5 – Fatigue crack initiation	8	3	5	120

Fig. 4. MATLAB interface for the FMEA analysis of the main girder

Once the input values are defined, the MATLAB script automatically determines the RPN values for all failure modes and ranks them from the most to the least critical. The program then generates a results table that summarises each failure mode together with its S, O, D, and RPN ratings. In addition to the numerical output, a bar chart is created to visually compare the RPN values and to easily identify the dominant failure mechanisms (Figure 5). Through this automated workflow, the MATLAB tool enables fast, transparent and reproducible evaluation of the FMEA results. The result facilitates decision-making, by indicating the failures modes that call for priority inspection, preventative maintenance, or more structural evaluation.

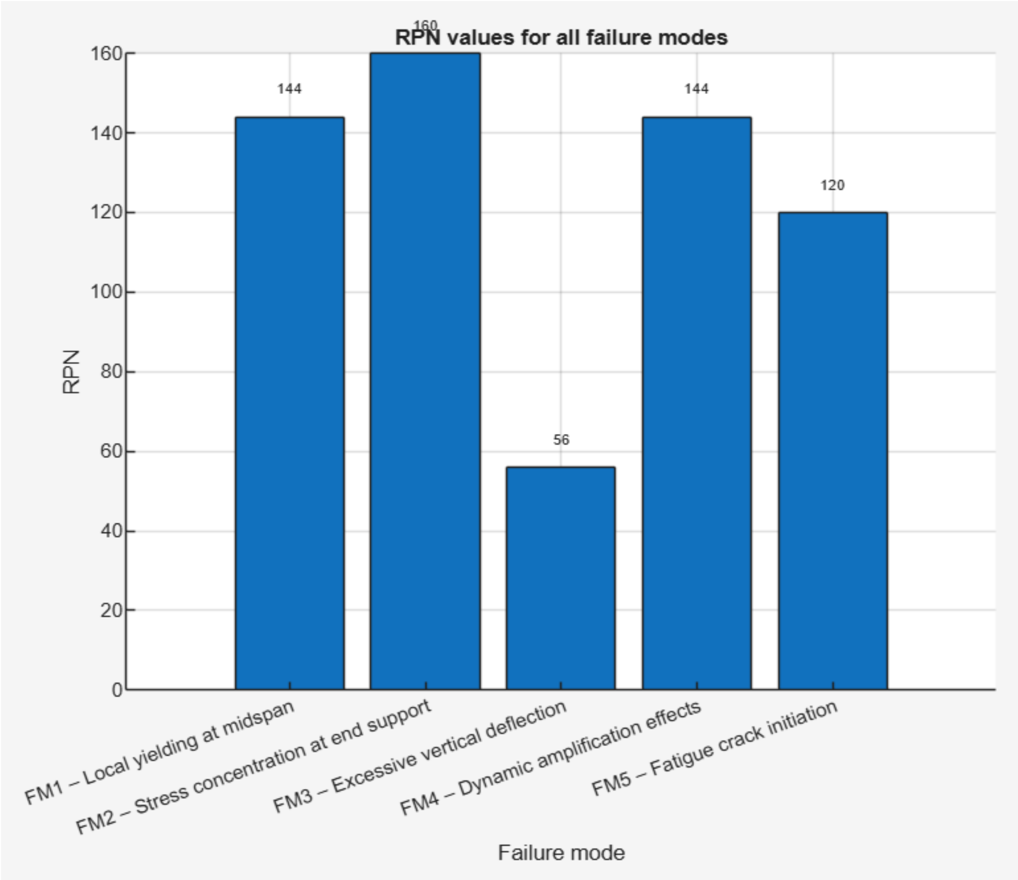


Fig. 5. Graphical representation of the computed RPN values

4. RESULTS AND DISCUSSION

Figure 4 shows the MATLAB interface developed for the FMEA of the crane main girder, where the user inputs the S, O and D ratings for the identified failure modes. Five failure modes were taken into consideration in the reference case: FM1 – local yielding at midspan, FM2 – stress concentration at the end support area, FM3 – excessive vertical deflection, FM4 – dynamic amplification effects, and FM5 – fatigue crack initiation. The initial ratings were assigned based on the numerical results and engineering judgement, considering the stress levels, deformation values, and the likelihood of detecting the damage during inspection. The calculated RPN values are summarized in the table within the interface and are shown graphically in Figure 5. The highest RPN value (RPN = 160) is obtained for FM2 – stress concentration near the end support, indicating that this area is the most critical in terms of severity, occurrence and detectability. This finding is consistent with the numerical simulations that revealed increased stresses and potential stress raisers around the end connections and welds. Local yielding at midspan (FM1) and the response under dynamic amplification effects (FM4) both result in RPN = 144, confirming that the midspan area under dynamic loading is also an important location that requires attention. Fatigue crack initiation (FM5) has a moderate RPN of 120. Although the fatigue life obtained from the numerical analysis is within acceptable limits, the possibility of crack initiation in highly stressed or welded areas should not be disregarded, particularly during long-term cyclic operation. In contrast, excessive vertical deflection (FM3) has the lowest RPN (RPN = 84), which reflects the fact that the calculated deflections remain well below the serviceability limits and can be easily identified by visual inspection or simple measurements.

Overall, the FMEA results indicate that the most relevant risks for the investigated crane girder are related to local stress concentrations and dynamically amplified loading, rather than global stiffness or deflection. The MATLAB tool provides a transparent and adaptable method to update the S, O and D ratings as new inspection data or improved numerical results become available. This facilitates the planning of targeted inspections, strengthening measures, or operational adjustments when necessary and makes it simple to reevaluate the risk ranking.

5. CONCLUSION

The FMEA conducted in this study shows that the most critical risks for the analyzed crane main girder arise from local stress concentrations and dynamically increased loading. This results from the input data acquired through the analytical and numerical analysis. The final FMEA evaluation is presented through a MATLAB tool, which provides a fast and transparent ranking of the failure modes and supports informed decisions regarding inspection and maintenance.

In conclusion, the results confirm that incorporating FEM indicators with the FMEA approach greatly enhances the reliability assessment and contributes to safer and more effective operation of bridge cranes. However, there is still room for improvement in this model. Future work may include the development of advanced MATLAB tools that automatically import FEM results, inspection data, and information from installed sensors. This would enable the parameters and risk level to be updated in real time. The same concept can also be applied to other components of the crane.

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