Fatigue Life Prediction and Strengthening Measures for Runway Girder Supporting Overhead Cranes in Industrial Mill: A Case Study

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Abstract. This study pivots the fatigue life prediction of a runway girder subjected to cyclic loading during the operation of an overhead crane in a steel mill. The load cases were created based on past records, and crane cycles were recorded using a counter sensor near the crawling path. The static forces per wheel were calculated according to the maximum capacity of the cranes, the cranes' self-weight, and the maximum working loads lifted during the operation. Moreover, a numerical analysis procedure was adopted to predict the average stress ranges in the runway girder due to the applied static loads under different conditions as per crane locations. Therefore, a finite element model was prepared using shell and line elements in CSI ETABS to determine and visualize stress ranges. Lastly, the fatigue life of the runway girder was predicted using a minor summation approach and verified by equivalent stress ranges. The study concluded that the fatigue life cycles of the runway girder are exceeded, and strengthening measures are required by providing longitudinal stiffeners with fillet partial penetration groove welds.

Keywords: Fatigue life, Structural assessment, Structural Strengthening

1 INTRODUCTION

Fatigue is a phenomenon in materials and structures that arises from repeated or cyclic loading. It is characterized by the initiation of cracks within the material, which occurs before reaching the ultimate stress point. These cracks develop gradually over time due to the cyclic nature of the loading. Unlike sudden failures, fatigue involves a cumulative process of crack generation under the repeated application of stress. The goal of studying fatigue is to understand and predict the point at which these cracks may compromise the material's integrity, leading to potential failure. According to failure theories, a component fails when the external stress exceeds the maximum value of tensile stress, maximum compressive stress or the maximum shear stress [1], [2]. Failure due to fatigue typically occurs significantly before reaching the maximum

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design stress [2]. Specifically, fatigue refers to changes in properties that occurs in metallic materials due to consistent application of strain and stresses, particularly to those changes which causes cracks or failure [3]. Similar to bridge structures, crane runway girders are also prone to experiencing the risk of fatigue in industrial steel structures [4]. The range of stresses encountered and also cycles number of transmitted loads affects the fatigue performance of the supporting structural elements [5]. In steel welded structures, fatigue crack often originates from welds. The cracks growth mechanism in each load cycle is explained by Broek [6]. During the welding process, the formation of minute metallurgical discontinuities occurs within the weld. These small irregularities, inherent to the welding process, become points of vulnerability. Consequently, cracks can develop from these discontinuities, contributing to potential structural weaknesses. [7]. Welds, particularly in the butt weld toes and in the roots of fillet welds, are commonly rough. These rough surfaces contribute to localized stress concentrations due to sharp changes in curvature.

There are two regions of fatigue life, as shown in Figure 1 of the AASHTO Fatigue Life Curve [8];

- Infinite life: Cracks due to fatigue are not expected to occur, and there is a constant amplitude fatigue limit (CAFL).
- Finite life: The cracking probability at the end of fatigue life is 2.5% or 97.5% probability of negligible fatigue cracking.

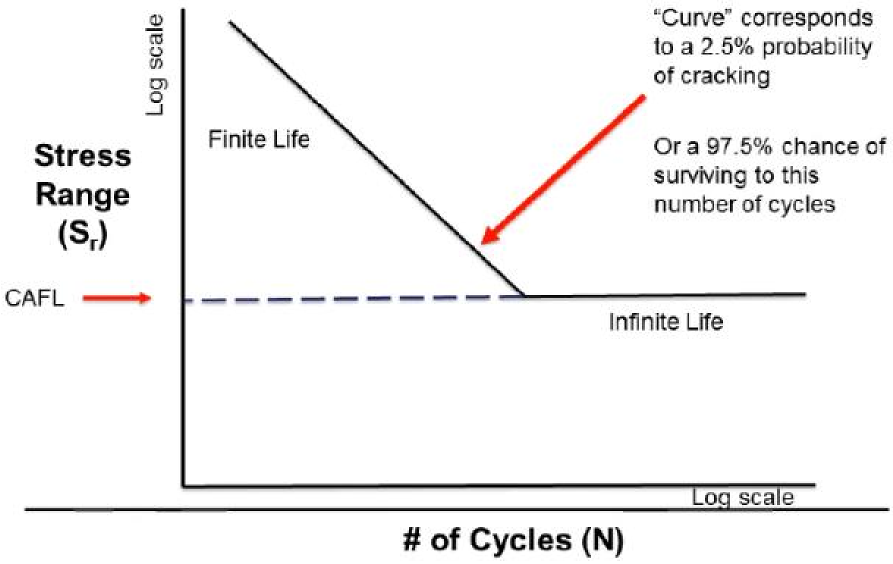


Fig. 1. AASHTO fatigue S-N curve [8]

The purpose of the fatigue assessment of an existing structure is to demonstrate that it can continue the safe operation over a stated residual service life. This assessment is mostly based on the outcomes of evaluating future risks and load impacts, as well as assessment of material properties and current geometry of the structure.

Wheels containing cranes are usually prone to significant external loads and operate in harsh environments, such as wind, rain, corrosion, high temperatures, and cyclic loadings, which result in the deterioration of material properties. When this deterioration reaches a critical point, structural fatigue may manifest, leading to a number of accidents that could cost lives and cause economic losses. Therefore, fatigue life assessment plays an important role in overhead crane structures.

1.1 CRANE RUNWAY DESCRIPTION:

An overhead crane, a prevalent material handling equipment employed in ports, docks, and mills, is the subject of this study, with a focus on the scrap loading crane depicted in Figure 2. This crane applies loads to various elements of the supporting structure. Figure 3 provides a schematic section of the runway girder consistently utilized in steel mills to support cranes, while the cranes characteristics are shown in Table-1. These structural characteristics of specifies elements are determined using measuring tools like a tap and vernier caliper by physical survey, and the load-carrying capacity of the cranes with their operational age is confirmed by the management of the steel mill.

The buildup section of the runway girder is composed of 10mm to 14mm thick plates, as shown in Figure 3, having a crane rail at the top flange of the girder attached with rail clips at 61 cm spacing. The stiffeners of two different lengths are attached alternatively to the upper flange. The stiffeners are connected with discontinuous welds to the top flange and side web plates and are not connected to the bottom flange. The quality of the weld is visualized as unhealthy and covered with corrosion, which may lead to microscopic imperfections.

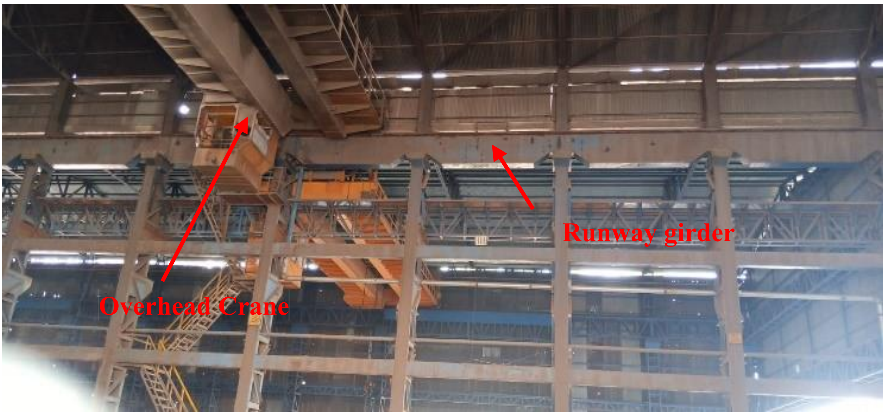


Fig. 2. Image of the Crane girder having overhead crane supported on columns bracket.

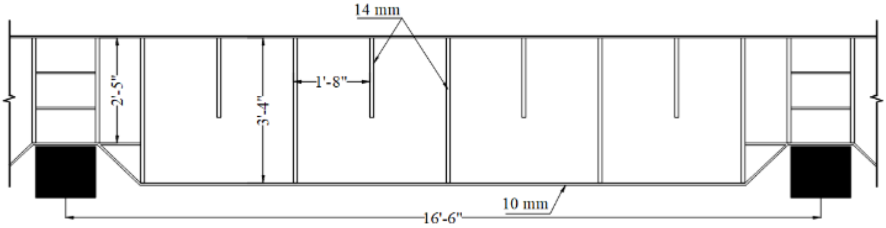


Fig. 3. Geometry of the Crane runway girder having box section with inner stiffeners

Table 1. Characteristics of runway girder.

Span of Runway Girder	16.33 ft
Material of Steel Members	ASTM A36
Operational Age	15 years
Daily Operational Hours	24 Hours
Crane -1 Capacity	40 Tons
Crane -2 Capacity	40 Tons
Crane -3 Capacity	15 Tons
Crane -4 Capacity	10 Tons

The number of crane cycles over the operational life of overhead cranes is achieved through the utilization of a sensor counter. A dedicated sensor for counting crane trips was installed along the crane's path, coupled with a camera for observation and verification of recorded trips. The cycles of the cranes were monitored for 48 peak operational hours. Sensor counters installed to count crane trips are shown in Figure 4.

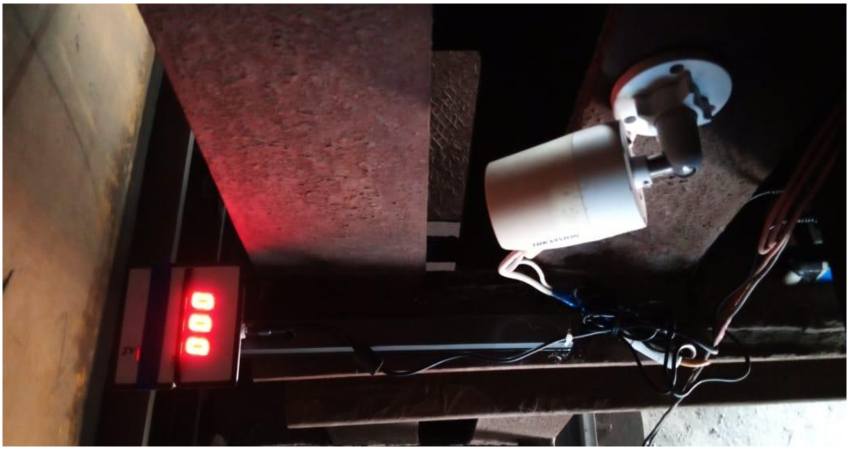


Fig. 4. Sensor counter installed near runway girder to count crane trips.

The data collected from the sensors is tabulated in Table 2

Table 2. Data of overhead crane cycles collected from Sensor counter.

Days	Time	Cumulative hours	Passing
1	3:40 pm	00	00
2	11:30 am	20	111
2	7:00 pm	27.5	130
3	11:00 am	43.5	213
Total Cycles in 48 hours		48	236
Total Cycles in 24 hours		24	118
Total Cycles in an hour		1	5

The analytically calculated loads on the supporting structure due to the crane's operational loads are tabulated in Table 3. The statical analysis approach adopted to determine the crane loads on the runway girder involves considering the self-weight of the crane bridge and trolley, wheel spacing, and the design load-carrying capacity of the crane. Vertical and side thrust factors are applied for consideration of dynamic effects, as per AIST TR-13 guidelines, which specify a vertical impact of 25% of the maximum wheel load for all crane types, and side thrust is 10% of the up-lifted load and crane self-weight [9]. The maximum wheel load reactions are determined by considering the crane lifted with its rated capacity, and the trolley and lifted weight are located near the runway girder.

Table 3. Analytically calculated overhead cranes reactions.

Cranes	Designed Capacity (Tons)	Vertical load (Tons)	Horizontal Thrust (Tons)
Crane 1 & 2	40	36.88	3.68
Crane 3	25	23.13	2.32
Crane 4	15	13.88	1.39

2 METHODOLOGY FOR FATIGUE LIFE ASSESSMENT:

The adopted methodology for fatigue life assessment is based on NSBA (National Steel Bridge Alliance) and AASHTO specifications [8], [10]. The well-known Pakistani steel mill in Hasan-Abdal was visited for the study of structural elements in the scrap movement and melting hall. Information was gathered through visual inspection and discussions with the steel mill management, including the number of cranes, their load-carrying capacity, material properties, working hours, and the age of the structure, as shown in Table 1. Overhead crane trips and cycle data per day were collected by preparing a sensor counter and installing it near the crane path, with a camera for the validation of cycle measurements.

Since the number of cycles was estimated from the installed sensor counter, and the stress ranges of each frame component were evaluated using the finite element model by applying key crane loading conditions. The S-N curve of the fatigue life given in the AASHTO specification was used to calculate the structure's lifespan. The curve is simply divided into a finite life and infinite life, as shown in Figure 1. The equation of this curve is:

$$N=A/Sr^{3} \tag{1}$$

$$Slope= -3$$

where,

N = Number of cycles
A = Detail Category Constant
Sr = Stress Range

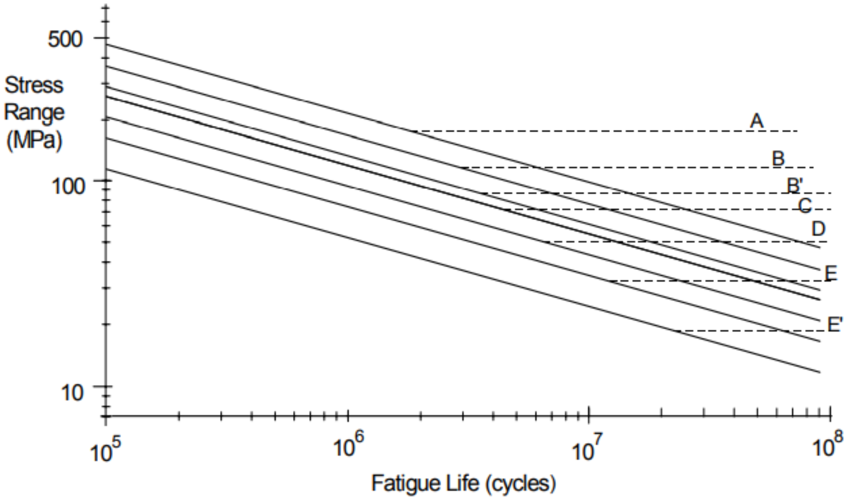


Fig. 5. S-N Curve as per ASSHTO Specification [8]

Fatigue life specifications in AASHTO classify commonly used steel bridge details into the category of fatigue which is A, B, B', C, C', D, E, and E', which are based on characteristics of fatigue. For the evaluation of existing riveted bridges and other steel members bearing cyclic loading, AASHTO provides additional information for fatigue classification. Detail Category for built-up members is provided in Table 4, whereas constants and threshold stresses for detail categories are provided in Table 5.

The MBE (Manual for Bridge Evaluation) recommends the base metal at net sections of riveted connections of existing bridges can be evaluated as C- Category detail over category-D in order to account for the riveted members internal redundancy [11]. NCHRP (National Cooperative Highway Research Program), The 721 Report gives additional recommendations for the fatigue resistance of riveted connections and tack welds [12]. The tack weld generally used in old riveted steel structures and their strength of fatigue has not been characterized in prior specifications. It was suggested that the tack welds assessed in C- Category details of fatigue over E- Category for 'base metal of intermittent fillet welds' as described in Specifications of AASHTO. Furthermore, the recommendation is also made for poor riveted conditions like missing or showing punching signs, the D-Category recommended [13].

Table 4. Detail Categories in AASHTO Specification [8].

General Condition	Situations	Detail Category
Build-Up Member	Base metal in component, without attachments, connected by: • Continuous full penetration groove welds with backing bars removed • Continuous fillet welds parallel to the direction of applied stress • Continuous full penetration groove welds with backing bars in place • Continuous partial- penetration groove welds parallel to the direction of applied stress	B B B' B'

Table 5. Detail category constants and threshold stresses [8]

Detail Category	Constant A Mpa	Threshold Stress Mpa
A	8.2E+12	165
B	3.93E+12	110
B'	2E+12	82.7
C	1.44E+12	69
C'	1.44E+12	82.7
D	7.21E+11	48.3
E	3.61E+11	31
E'	1.28E+11	17.9

2.1 NUMERICAL STRESS ANALYSIS

The method of finite element analysis is famous for entirety of the studied domain, in which the members are discretized into discrete finite elements, interconnected at nodal points along element boundaries. This discretization allows for a comprehensive approximation of the solution across the entire domain. The approach involves formulating an approximate solution over each element matrix, which is then assembled to derive the stiffness matrix, as well as displacement and force vectors for the complete domain.

In the specific context of this study, finite element modeling is conducted using the ETABS software. The modeling of the runway girder involves the utilization of 4-node quadrilateral shell elements. As per the structure, the girder is continuous for 23 spans supported by buildup brackets with a distance of 16.33 ft c/c, attached by fillet weld to each other from the bottom of the girder flange, behaving much a simple supported beam. For the evaluation of the structural behavior of girders, boundary conditions are considered as hinge at the ends of beam nodes. This facilitates a detailed and accurate representation of the structural behavior under load consideration in different cases.

Case 1: Crane 1 or 2 is in the middle of the girder and imposes loads of 36.88 tons and 3.68 tons vertical and horizontal thrust, respectively. Stresses are found to be 20.6 Kips/in^2 and 3.12 Kips/in^2 maximum and minimum, respectively.

Case 2: Crane 3 is in the middle of the girder and imposes loads of 23.13 tons and 2.32 tons vertical and horizontal thrust, respectively. Stresses are found to be 14.25 Kips/in^2 and 2.5 Kips/in^2 maximum and minimum, respectively.

Case 3: Crane 2 and 3 are closed and nearly in the middle of the beam, imposing maximum loads of 36.88 tons and 23.13 tons, respectively. Stresses are found to be 21.2 Kips/in^2 and 4.4 Kips/in^2 maximum and minimum, respectively.

Case 4: Crane 1 and 2 are closed and nearly in the middle of the beam, imposing maximum loads of 36.88 tons and 36.88 tons, respectively. Stresses are found to be 22.9 Kips/in^2 and 5.3 Kips/in^2 maximum and minimum, respectively.

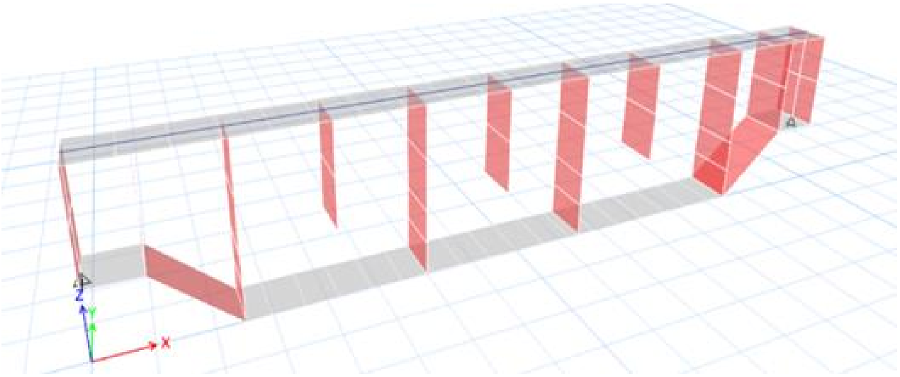


Fig. 6. FEM runway girder with internal stiffeners.

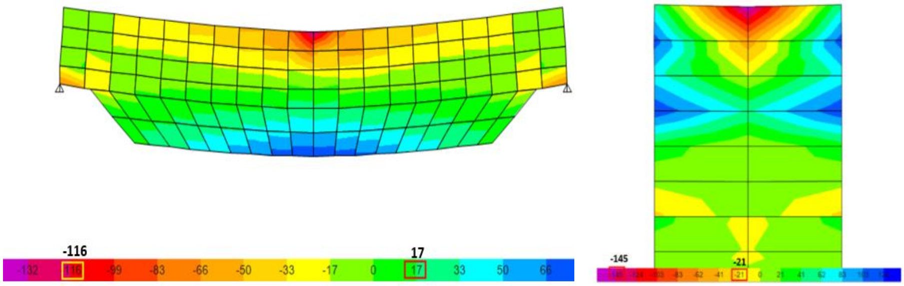
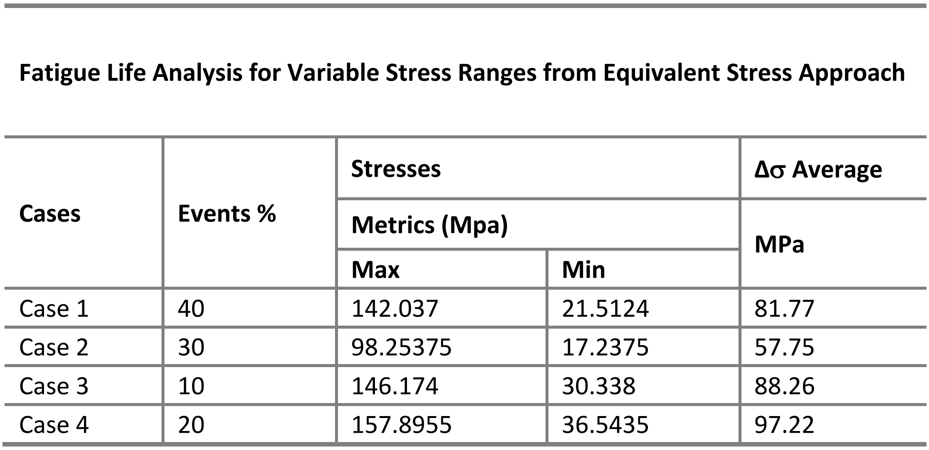


Fig. 7. Stresses in Outer Box and internal stiffeners of the girder in Case 1.

Table 6. Average stresses in different scenarios of cranes loading in Runway Girder.



Fatigue Life Analysis for Variable Stress Ranges from Equivalent Stress Approach

Cases	**Events %**	**Stresses**		**Δσ Average**
		Metrics (Mpa)		**MPa**
		Max	**Min**	
Case 1	40	142.037	21.5124	81.77
Case 2	30	98.25375	17.2375	57.75
Case 3	10	146.174	30.338	88.26
Case 4	20	157.8955	36.5435	97.22

3 RESULTS AND DISCUSSION

The analysis has yielded the following outcomes:

$$N = (5\text{cycles/hour})\ (24\ \text{hour/day})\ (7\ \text{days/week})\ (52\ \text{week/year}) \tag{2}$$

$$(15\ years) = 655200\ cycles$$

$$Total\ cycles\ of\ all\ cranes = 4 * 655200 = 2620800\ cycles.$$

According to the AASHTO specifications, the built-up member detail falls under Category B’.
From figure 5, from Detail B’- category line at N = 2620800 cycles, to found that the permitted stress ranges are approximately 110 MPa. Furthermore, the Fatigue life properties of the runway girder detail is measured by using equivalent stress range due to the number variable stress ranges and is shown in Table 7.

Table 7. Fatigue life Calculation for runway girder from equivalent stress range.

ni cycles	**Ni cycles**	**ni/Ni**	**γi = ni/TC**	**γi Δσ^3**
1048320	3657406	0.287	0.4	218734.3
786240	10386584	0.076	0.3	57766.8
262080	2909359	0.090	0.1	68743.7
524160	2176556	0.241	0.2	183776.6
	Sum ni/Ni	0.69	Sum γi Δσ^3	529021.4

Since for all events miner summation in the history of loading is 0.69, which means 69% of the fatigue life of the runway girder has been enhanced.
Let’s check from equivalent stress range method,

$$\Delta\sigma e = [\Sigma\gamma i\Delta\sigma i^{m}]^{1/m}$$

$$\Delta\sigma e = [\,529021.4]^{1/3} = 80.88 \text{ MPa}$$

$$N = M\,\Delta\sigma r^{-3} = (20*1011)\,(80.88)-3 = 3780565.69 \text{ cycles}$$

Fatigue life expended =2620800/3780565.69 = 0.69 = 69%.

So, the number of cycles expended by the Box girder outer plates and inner stiffeners from total life cycles is 69%.

Thus, the fatigue life analysis for the overhead crane runway girder revealed a total of 2,620,800 cycles expended over a 15-year operational period. The structural category was determined to be Category B' according to AASHTO specifications. Miner Summation showed that 69% of the girder's fatigue life had been utilized, and verification through the equivalent stress range method estimated a remaining fatigue life of 31%.

4 CONCLUSION

This comprehensive research thoroughly explores the fatigue life prediction of an overhead crane runway girder, encompassing historical load case analysis, precise crane cycle monitoring, and numerical simulations via the finite element method in CSI ETABS. Calculations considering static forces per wheel and stress ranges under various conditions unveiled a critical state, indicating near-exhaustion of the girder's fatigue life cycles. Weaknesses were identified in the irregular geometry and non-continuous weld connections of the stiffeners, categorizing them as fatigue-resistant and falling short of AASHTO and NSBA standards for fatigue loading. Strengthening measures are imperative, proposing the incorporation of longitudinal stiffeners with fillet partial penetration groove welds, which is more likely behaves as an I-Section and the continues groove weld for the existing stiffeners, these measures will enhance structural resilience of the girder and minimize the stress concentration. Furthermore, the fatigue life evaluation, employing the Miner Summation and equivalent stress range methods, concurred that 69% of the girder's fatigue life has been utilized. Specific loading conditions for diverse crane configurations revealed average stress of 80.88 Mpa, leading to an overall fatigue life cycles determination of 3780565.69 cycles, categorizing it as AASHTO's Category B' as per Table 4 and 5. These findings underscore the exigency for periodic assessments, guidance for fatigue life prediction for runway girders, and informing structural remedial strategy.

References

1. A. Yasir, “Improving the fatigue life of steel bars by using Nano-coating technology,” International Journal of Engineering & Technology, vol. 3, no. 4, p. 523, Nov. 2014, doi: 10.14419/ijet. v3i4.3493.
2. U.P. Shine, E.M.S Nair, “Fatigue failure of Structural Steel analysis using Fracture Mechanics,” International Journal of Mechanical and Mechatronics Engineering, vol. 2(10), pp. 1159- Available: https://www.researchgate.net/publication/242569600
3. R. Buczkowski and B. Żyliński, “Finite element fatigue analysis of unsupported crane,” Polish Maritime Research, vol. 28, no. 1, pp. 127–135, Mar. 2021, doi: 10.2478/pomr-2021-0012.
4. K. Kashefi, A. P. Zandi, and M. Zeinoddini, “Fatigue life evaluation through field measurements and laboratory tests,” in Procedia Engineering, Apr. 2010, pp. 573–582. doi: 10.1016/j.proeng.2010.03.062.
5. K. Kwon, “Reliability Assessment, Performance Prediction and Life-Cycle Management of Fatigue Sensitive Structures Based on Field Test Data,” 2011.
6. Heath, W G. “The Practical Use of Fracture Mechanics. D. Broek Kluwer Academic Publishers, Dordrecht, 1988. 522 Pp. Illustrated. £69.50.” The Aeronautical Journal, vol. 93, no. 924, 1 Apr. 1989, pp. 151–151,
7. R. Jones, “Fatigue crack growth and damage tolerance,” Fatigue and Fracture of Engineering Materials and Structures, vol. 37, no. 5. Blackwell Publishing Ltd, pp. 463–483, 2014. doi: 10.1111/ffe.12155.
8. American. AASHTO LRFD Bridge Design Specifications. Washington, D.C., American Association of State Highway and Transportation Officials, 1999.

9. AIST, Technical Report 13 (2021 Revision). Guide for the Design and Construction of Mill Buildings, Association for Iron & Steel Technology (AIST), 10 June 2021.
10. J. W. Fisher, G. L. Kulak, and I. F. C. Smith, “National Steel Bridge Alliance A Fatigue Primer for Structural Engineers,” 1998.
11. Aashto, “The Manual for Bridge Evaluation, Third Edition, 2017, with 2018, 2020, and 2022 Interim Revisions and November 2021 Errata - Table of Contents and Introduction,” 2018. [Online].
12. H. G. Downs, Criteria for evaluation of truck weight enforcement programs. Transportation Research Board, National Research Council, 1981.
13. Fhwa, “Design and Evaluation of Steel Bridges for Fatigue and Fracture REFERENCE MANUAL,” 2016. [Online].