

Fatigue Analysis and Assessment of a State Highway Bridge on Hunsur-Mysore Road

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Abstract India's road transport system relies heavily on its extensive network of bridges, many of which are reinforced cement concrete RCC structures. Fatigue is a critical issue for these road bridges, significantly influencing their life span. This study focuses on the fatigue analysis of an RCC bridge on NH275, connecting Mysore to Hunsur in Karnataka State, India to ensure the long term safety and reliability of aged RCC road bridges by assessing their structural integrity in the face of fatigue induced damage. The methodology involved a systematic approach by collecting load data to calculate annualized traffic and cross-sectional data was gathered from documentation to accurately model the bridge. A moving load analysis was conducted to evaluate the stress distribution under vehicular loads. The study then applied Linear Elastic Fracture Mechanics (LEFM) to analyze fatigue cracks caused by cyclic loads using crack initiation and propagation theories. But, due to the high randomness of LEFM parameters and associated uncertainties, structural reliability principles were incorporated and the Reliability Index (β), was calculated using a limit-state approach. MATLAB 7.12.0 (R2011a) was used for computational analysis which enabled precise calculations. This study provides a detailed understanding of the relationship between load cycles, crack size, and the Reliability Index (β) for Reinforced Concrete Bridge. It emphasizes the importance of equivalent stress range and detected crack size in fatigue analysis and offers a methodology for predicting bridge reliability over time. The results indicated that the Reliability Index (β) consistently decreased as the number of load cycles increased. At 2×10^6 cycles, the highest β value was

observed in the scenario with a single moving vehicle, reflecting lower stress levels. The analysis also showed that bridges with detected cracks and varying traffic growth exhibited different β values depending on the crack size and vehicle speed. This developed method enabled the assessment of bridge dependability and helped determine an acceptable risk level and optimal inspection intervals, ensuring a safe and reliable bridge. The findings contribute to the development of more accurate inspection strategies and maintenance plans, ensuring the safety and longevity of bridge structures.

Keywords Fatigue Analysis, Linear Elastic Fracture Mechanics, Moving Load Analysis, RCC Bridge, Reliability Index (β), Structural Reliability

1. Introduction

Bridges are fundamental structures that play a vital role in transportation networks by connecting regions and facilitating the movement of people and goods. They overcome physical barriers such as rivers, valleys and other transportation routes, making them critical to contemporary infrastructure. In India, a significant number of bridges that are over fifty years old remain in active use. As transportation networks evolve, higher traffic loads and increased intensity of vehicles demand greater efficiency. Thus these structures are subjected to stricter performance criteria [1]. These instances illustrate the critical need of understanding concrete fatigue. Several bridges in use

today were designed and constructed with the standards and materials of their time, which may not meet the current demands of traffic and load intensity. The growing vehicular loads, coupled with environmental factors, exacerbate the stress on these structures. As these bridges age, the materials deteriorate, and the risk of fatigue failures increases, posing safety concerns and operational challenges [2]. Replacing old bridges with new ones is often considered a straightforward solution to address these issues. However, the financial implications of such an undertaking are significant. The costs associated with demolition, construction, and the resulting disruptions to traffic and local economies make this option less feasible in many cases [3]. Therefore, there is a pressing need to explore alternative solutions that extend the service life of existing bridges without compromising safety or performance.

Bridges are susceptible to different kind of loads throughout their life. The dead load resulting from its self-weight remains constant forever and exerts a consistent force on the structure [4]. However, live loads due to vehicle weights are variable and unpredictable. Currently, bridges undergo serious conditions that could lead to fatigue and eventually visible signs of deformation as a result of the modern increase in axle loading and heavy traffic flow frequency [5]. The materials used in constructing bridges have been improved over time in order to meet not only present but also future requirements thus contributing towards sustainable development in global infrastructure.

Fatigue behavior in materials is a critical one in the field of structural engineering, especially when constructing infrastructures like bridges that are vulnerable to repetitive loading for long periods [6]. It describes the progressive, inherent and irrecoverable changes in the material due to its repeated loads. Fatigue in concrete starts with shrinking-induced micro cracks that develop during hardening [7]. The aggravation of these micro cracks due to cyclic stresses leads to fatigue damage occurring at much lower stress levels than those obtained from static failure analysis at ultimate strength. As a result, fatigue damage is a significant threat to the longevity and safety of structures. Therefore, a better comprehension of these risks has been achieved by classifying fatigue phenomena into high and low cycle fatigue [8]. Moreover, fatigue life which refers to the time period that a material can last in cyclic loading before fracturing can be studied by many different methods. The stress-life method (S-N curve approach) explains the number of cycles that a material can endure before failure is primarily determined by the stress amplitude it experiences [9]. In addition to this, there is also a strain-life method that determines how the material will react under repeated strains and a crack propagation technique based on Fracture Mechanics which describes how cracks grow during each cycle of load application [10]. These techniques provide information about the mechanical behavior associated with fatigue of materials guiding their

design, maintenance and rehabilitation purposes in relation to critical structure.

The fundamental theory of fracture, known as Linear Elastic Fracture Mechanics (LEFM), was initially formulated by Griffith and later refined by Irwin and Rice. This helps in understanding how cracks initiate and propagate under cyclic loading, ultimately aiding in the assessment and design of concrete structures to withstand fatigue [11]. The theory that addresses the behavior of sharp cracks in elastic materials, is relatively straightforward. Hence, LEFM principles are utilized in predicting fatigue life of concrete. Concrete also presents additional challenges due to a substantial process zone ahead of the crack tip. Despite these complexities, there are some uncertainties in engineering choices which include certain level of ambiguity, lack of experience and the inherent variation in design elements such as yield strength, loads and dimensions [12]. Uncertainties can be broadly divided into, random variables denoting the response of a structure e.g. its strength or resistance and random variables representing the effect of loading on a structure or load effect. A Linear Elastic Fracture Mechanics (LEFM) method is recommended as an alternative to AASHTO method as it fails to integrate fracture size data. It was suggested that LEFM could be used as an alternative to AASHTO in assessing fatigue-reliability evaluation of steel bridges.

Although these variables are random, they demonstrate statistical regularity and are best studied using Probability Theory which is concerned with measuring uncertainties arising from random experiments. This theory assists in finding out the 'probability of failure' for a structure. Given the highly random nature of the parameters involved, the risk and uncertainty in the developed model are analyzed using the Latin Hypercube sampling technique. This technique aids in accurately assessing the reliability of a structure by effectively sampling and analyzing the random variables involved [13]. Accordingly, several researchers proposed a compound sampling to calculate the probability of fracture using Latin Hypercube Sampling (LHS) [14] and developed a methodology for damage assessment of fatigue and to monitor the reliability of the bridge [15], [16]. The concrete fatigue model is founded on the viscoelastic properties of composite materials, and shows the actual behaviour of concrete under cyclic compression. This is an easy approach for predicting the remaining life of a concrete bridge under the fatigue load and rheological changes in the material [17].

The analysis and design of bridges often rely on various approaches such as analytical methods like Miner's rule [14], [16] and the S-N Curve [18], computational techniques including Finite Element Analysis (FEA) [19] and software like ANSYS [5], [20], [21] or STAAD Pro [22], and numerical methods such as Latin Hypercube Sampling (LHS) [23] and Monte Carlo simulations [24], [25]. Analytical methods are prized for their reliability based on stress-strain histories and their straightforward

application without iterative processes. However, they may not provide exact clarity and can be challenging for complex bridge structures. Computational methods excel in handling vast data and identifying critical loading points but require substantial computational time and can be prone to convergence issues. Numerical methods offer precise outputs but are time-consuming and can struggle with optimization tasks [26]. Each approach thus offers distinct advantages and limits, making their selection critical based on the specific needs and challenges of the bridge design and analysis process.

Since different methods from all the approaches have considerable merit in corresponding studies, a blend of analytical, statistical and computation modelling approaches is considered for the present study to develop a computational model to analyze the life of a pre-existing bridge under fatigue using S-N curve approach and use linear elastic approach (LEFM), to calculate the intrinsic safety factor against fatigue failure in an existing bridge. Thus a process for evaluating an existing bridge's fatigue based on dependability has been developed to provide the best possible inspection of bridges for fatigue behavior. The current study focuses on analyzing the fatigue behavior of the bridge located on NH275 shown in Figure 1 using fracture mechanics. The reliability of the bridge is assessed by applying probability theory to evaluate uncertainties related to its performance. The objective of this study is to determine the inherent safety rating of the highway bridge, particularly in assessing fatigue and potential structural wear.



Figure 1. Bridge connecting Mysore and Hunsur-Madkeri Road

2. Materials and Methods

The fatigue life and structural integrity analysis include data collection, material testing, load assessment, and fatigue life estimation. An accurate data collection of the old bridge for its fatigue analysis is crucial. The detailed information about the bridge's design, construction

materials, age, traffic data and maintenance history of a RCC bridge is considered for the purpose. The existing bridge on the Hunsur - Mysore highway was taken for the present study and all the essential information regarding the bridge was collected from the Karnataka Road Development Corporation Ltd (KRDCL) and Public Works Department (PWD) for the study. Fatigue limit state is the criteria adopted for the selected existing bridge to ensure that the bridge can endure repeated load cycles over its lifetime and without significant degradation of materials or risk of failure. Also, according to the Indian Road Congress code, the potential load combinations are defined and the moments are derived from the STAAD Pro. Software for calculations.

The overall study was conducted in accordance with IRC: 6 – Standard Specifications and Code of Practice for Road Bridges, Section II: Loads and load combinations (Latest Revision) [27], IRC:21 – Standard Specifications and Code of Practice for Road Bridges, Section III: Cement Concrete (Plain and Reinforced) (Latest Revision) [28], IRC:112 – Code of Practice for Concrete Road Bridges (Limit State Design) [29] and IS 456:2000 – Code of Practice for Plain and Reinforced Concrete [30].

2.1. Bridge Details

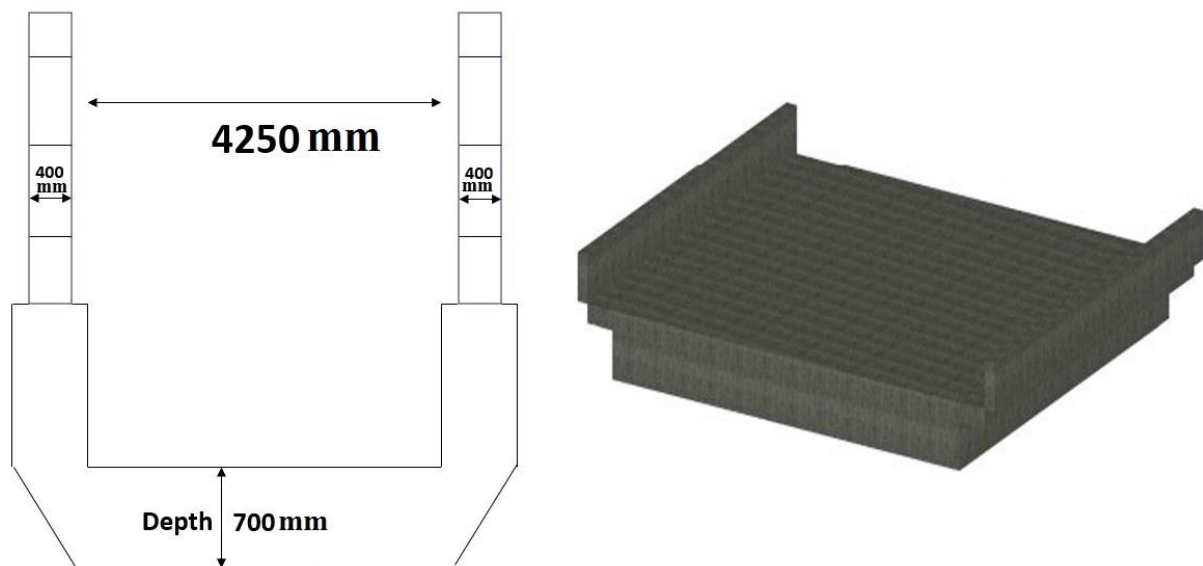
Specific details of the bridge are essential to provide a thorough assessment of its current condition and offer practical recommendations to improve its performance and prolong its service life. For the present study, a reinforced concrete bridge with three spans of 21m/c each, located on Hunsur-Mysore road is considered. The comprehensive details of the bridge, including design and structural characteristics, form the foundation for the fatigue analysis and assessment process of the bridge which are shown in the Table 1 and the Figure 2 shows the cross-section details of the bridge.

2.2. Vehicle Configuration Data Gathering

The configuration of each vehicle acts as the moving load, making it a crucial input for fatigue analysis. This configuration is predetermined. The survey was conducted in accordance with IRC: SP: 72 – 2007 [31] guidelines, which specify that only motor transportation having a total mass of 3 tonnes or more is to be used to calculate design traffic, excluding a substantial number of cars, two-wheelers, and light weight vehicles. Table 2 provides a list of vehicles recorded during the traffic count.

Table 1. Bridge Details

SI No	Parameters	Details
1.	Location	Hunsur, Mysore-Madikeri Highway (NH-275)
2.	Type	Slab Culvert, RCC bridge
3.	Overall Span	21m
4.	Distance b/w Piers	7m
5.	Material Specifications	M20, Concrete Bridge
6.	Year of Construction	2007
7.	Maintenance History	No modifications / Maintenance carried out after construction
8.	Deck Width	7.5 m
9.	Environmental Condition	Normal condition

**Figure 2.** Cross section details of the bridge**Table 2.** Vehicle's Technical Specifications

Vehicle Class		BUS (BS)	Two-Axle Truck (2AT)	Multi-Axle Truck (MAT)
Geometrical Details of the vehicle	Vehicle Name	LPT 1613	LPT 2521	Tata LP 1512 TC
	Wheel base (m)	4.225	4.165 & 1.43	5.895
	Total length (m)	7.38	9.26	10.025
	Width (m)	2.115	2.44	2.434
	Kerb Weight (kN)	44	60.36	40.13
	Gross weight (kN)	158.8	245	145.63
Vehicle Load Information	Front axle load-FAW (kN)	16.3	14.5	14.85
	Rear axle load-RAW (kN)	27.7	45.87	25.28
	Max Permissible-FAW (kN)	58.8	58.8	46
	Max Permissible -RAW (kN)	99.96	186.2	99.63

2.3. Vehicle Traffic Data

Vehicle information has been gathered over a predetermined year-long period on this route. To create a load spectrum, representative vehicle loads have been identified using the statistical analysis of the data. The term "load spectrum" is frequently used to refer to the fatigue loads on a structure in service. The created load spectrum can be used to prepare reliability-based predictions of the fatigue life of these bridges as well as fatigue investigations on them. The load spectrum will be helpful in arriving at optimum inspection intervals for bridges.

Detailed traffic data, including vehicle types and frequencies is necessary for estimating the loads the bridge experiences over time. Traffic data for NH275, from Mysuru to Madikeri, was collected through periodic traffic censuses and sample surveys, which were meticulously carried out at regular intervals along the road. Table 3 presents the compilation of vehicles noticed counting. Over a five year period, this data was compiled and cross-referenced with information from the public works department to ensure accuracy and completeness.

Table 3. Traffic data collected

SI No	Vehicle Type	Traffic Data for the year				
		2018	2019	2020	2021	2022
1	Bus	550	600	585	642	589
2	Two Axled Truck	960	878	750	869	728
3	Multi Axled Truck	410	425	450	513	456

2.4. Vehicle Combinations

In the field of transportation, a variety of vehicle combinations are used to transport heavy loads. Common pairings include buses (BS), multi-axle trucks (MAT), and axle trucks (AT), as defined by the user in these studies. These studies also involve analyzing moving loads with different user-defined combinations, such as loaded and unloaded vehicles. The challenge intensifies when

examining a bridge's dynamic response to multiple axle loads simultaneously crossing it. Factors influencing the dynamic response includes axle numbers, axle arrangement, spacing, and loads. Table 4 illustrates the different possible combination of single vehicles under loads and non-load generated for the study.

Table 4. Vehicle combination under loads and non-load used for the study

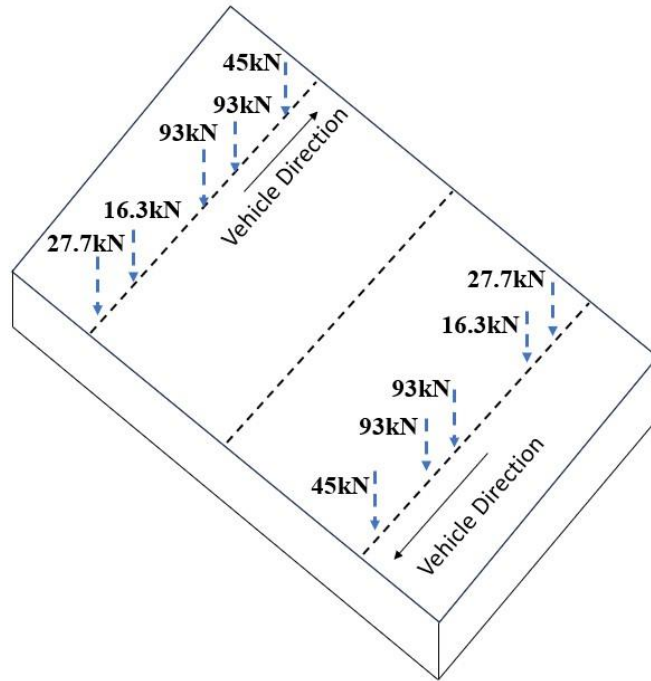
List of vehicle combination	
1. LMAT + ULMAT	9. LBS + ULBS
2. LMAT + UL2AT	10. LMAT + L2AT
3. LMAT + ULBS	11. LMAT + LBS
4. L2AT + ULMAT	12. L2AT + LBS
5. L2AT + UL2AT	13. ULMAT + UL2AT
6. L2AT + ULBS	14. ULMAT + ULBS
7. LBS + ULMAT	15. UL2AT + ULBS

2.5. Moving Load Analysis

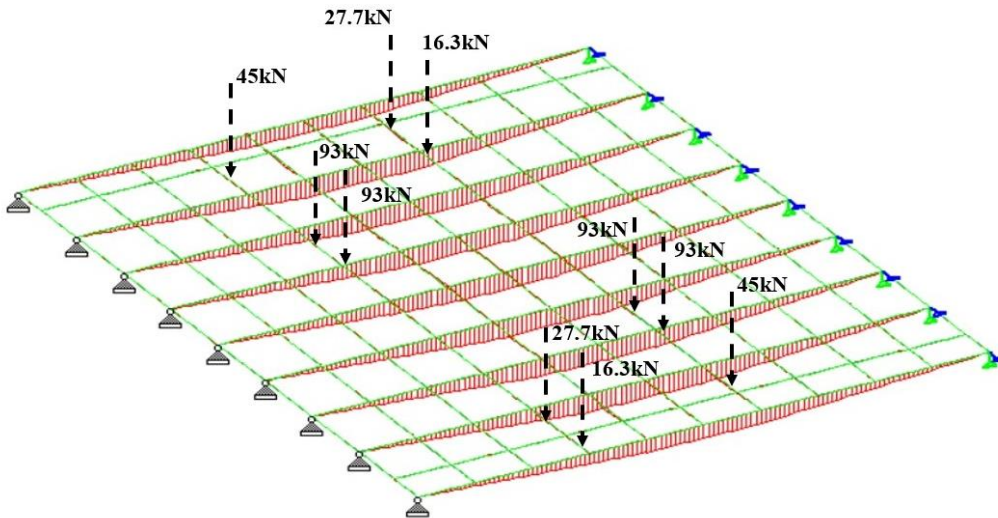
Moving load analysis is a process that involves evaluating various loading scenarios along the entire route of the moving load to determine the maximum and minimum force or stress on the bridge [32]. To analyze the moving loads, the process begins by specifying the vehicle loads, traffic lanes or surfaces, along with the load application. Statistical analyses are conducted using unit loads on lanes at different points in order to determine the influence line or influence surface. These results are generated as vehicles move across the structure. Figure 3 illustrates the example of live load analysis of the bridge under the load combination LBS + ULBS. Similarly, all the combinations of loads are analyzed in this study.

2.5.1. Assumptions for Analysis

Fast Moving Vehicles are the vehicles traveling at 50 km/h with a clear spacing of 2 meters between them. Slow moving vehicles are the vehicles moving at 25 km/h with a clear spacing of 1.5 meters and single moving vehicles are those individual vehicles moving across the structure.



3a. Load applied on the bridge Slab



3b. Bending movement of the vehicular load on the slab

Figure 3. Live load analysis of Hunsur Bridge under the load combination LBS + ULBS

2.6. Cycles Counting Method

To classify and distinguish the stress range, cycle counting technique is used. The damage for the whole structure is aggregated by combining the damage from each range. To determine the equivalent impact of moving loads, Miner's rule is combined with rain flow counting and the life estimates are calculated using the Palmgren-Miner rule along with a counting cycles approach.

To estimate the life of a component under varying loads, the complex load data is simplified into constant amplitude events and the rainflow-counting method is used to reduce the stress variation spectra into simple stress reversals, enabling the use of Miner's rule for fatigue life assessment. In this investigation, MATLAB rain flow counting technique is used, following the American Society for Testing and Materials (ASTM) Standards for managing complex load histories.

2.6.1. Equivalent Number of Cycles

Equivalent number of cycles (N_{eq}) fatigue life of a bridge under varying stress conditions. The stress range (S_r) is determined by subtracting the minimum stress (S_{min}) from the maximum stress (S_{max}), as shown in the Equation 1.

$$S_r = S_{max} - S_{min} \quad (1)$$

The equivalent cycle ratio (B) normalizes (N_{eq}) by its mean value, as described in the Equation (2).

$$B = N_{eq}/N_{eq}(\text{Mean}) \quad (2)$$

N_{eq} is further calculated using Equation (3), which relates the stress range to the slope of the S-N curve. This process helps in estimating the fatigue life by considering the effects of both live and dead loads on the bridge.

$$N_{eq} = 1 + [S_r/S_{rmax}]^m \quad (3)$$

2.6.2. Equivalent Statistic Stress Range

The annualized equivalent stress range is calculated using the stress ranges and traffic data. In practice, the loading on the girder is not a simple cyclic constant amplitude stress, instead, it consists of variable amplitudes and frequencies that do not repeat. Through Miner's cumulative damage concept, these varying amplitudes are transformed into an equivalent constant amplitude. The concept is that the fatigue damage caused by this related

stress range is equivalent to that caused by a sequence of stress ranges with varying amplitudes. The corresponding static stress range is determined accordingly and the equivalent stress determining the formula is provided in the Equation (4), where P_i represents the frequency of occurrence for each stress range (S_i), B is the number of stress ranges and m is S-N curve slope.

$$S_{RS} = \sum_{i=1}^B [P_i \times S_i^m]^{1/m} \quad (4)$$

2.7. Fatigue Evaluation Procedure

The fatigue behaviour of the selected bridge is analyzed focusing on the initial crack ' a_i ', and its crack size ' a_d ' during inspection. The evaluation process follows a step by step procedure, with the calculation of the fatigue crack propagation rate using Paris' Law. Component's dimensions and constant amplitude stress range determine the stress intensity factor range (ΔK). The fatigue life is then estimated considering, crack's initial and final sizes. The stress intensity factor (SIF) is particularly considered for edge cracks, which typically initiate at the bottom of the concrete structures and are subjected to bending loads. Flow chart for the evaluation of the bridge is depicted in the Figure 4.

2.8. Latin Hyper Cube Sampling Technique to Determine Inherent Safety Level

The fatigue reliability analysis determines the probability of failure of the bridge through the latin hyper cube sampling technique. The inherent randomness in determining the fatigue life is reflected in the use of random variables, initial size of the crack (a_i), crack size detected (a_d), growth parameters of the crack (C and m), Equivalent stress range (S_e) and stress modelling parameters (B_m). Using MATLAB, random values for these variables and the final size (a_f) are determined under a given stress level.

By iterating this process multiple times, the required number of cycles for the crack propagation to reach (a_f) is determined and the probability of failure (P_f) is calculated as the ratio of failure cases to total stimulations. The Reliability index (β) is then derived using the cumulative distribution function of a standard normal variable.

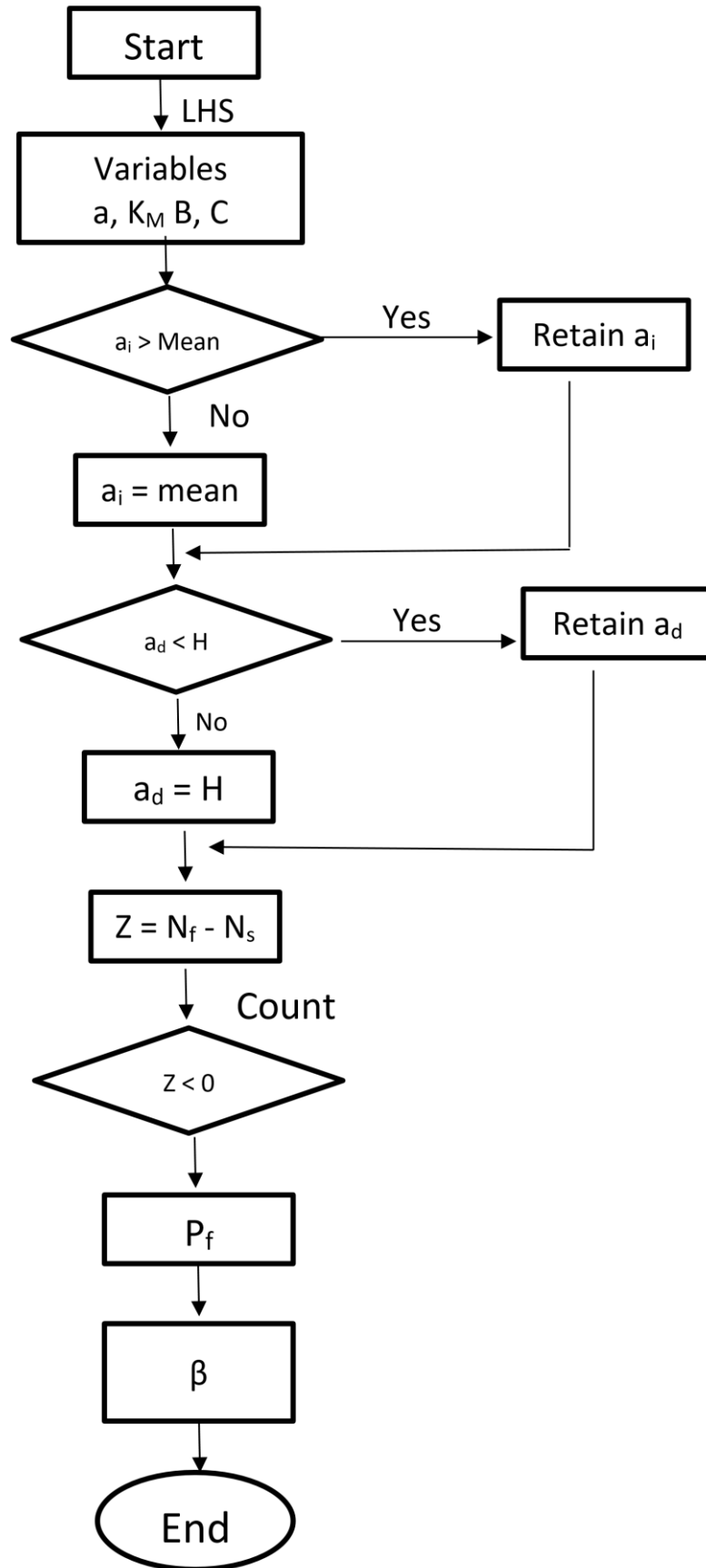


Figure 4. Flowchart for bridge evaluation

3. Results and Analysis

3.1. Moving Load Analysis

Moving load analysis is a process that involves evaluating various loading scenarios along the entire route of the moving load to determine the maximum and minimum force or stress on the bridge. Statistical analysis of Hunsur Bridge was carried out using the finite element method in STAAD pro civil. The unit loads subjected to the traffic lanes or surfaces at different points determine the

influence line or influence surface. These results are generated as vehicles move across the structure.

Response of the support, plate elements, forces on the truss beams and nodal displacements of the structural model are among the outcomes that can be computed for influence lines or surfaces. Three different forms of vehicle motions are analyzed in this study i.e., single vehicle, fast moving and slow moving vehicle. Figs 5, 6 and 7 present the bridge's stress variation for single vehicle situation, combinations of fast moving vehicles and combinations of slow moving vehicles respectively.

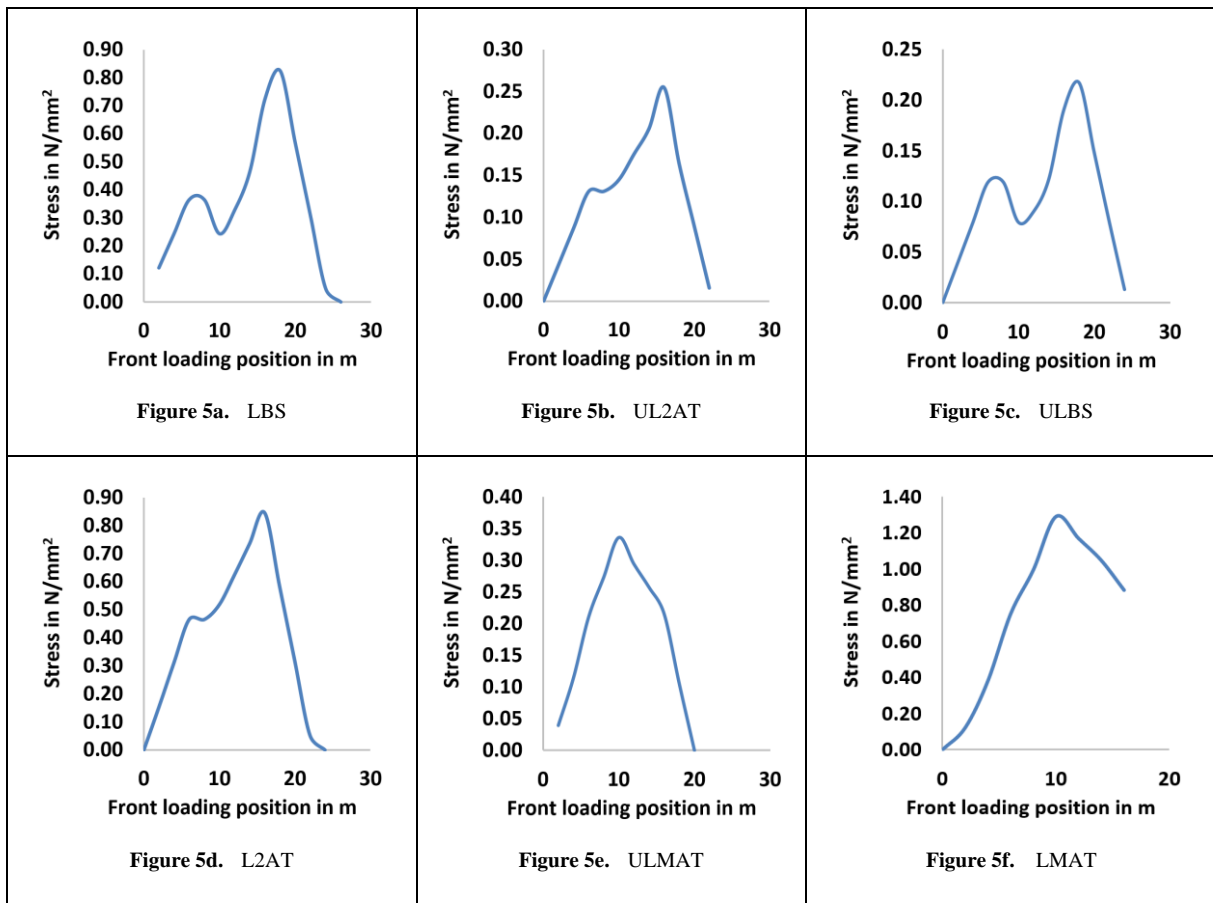
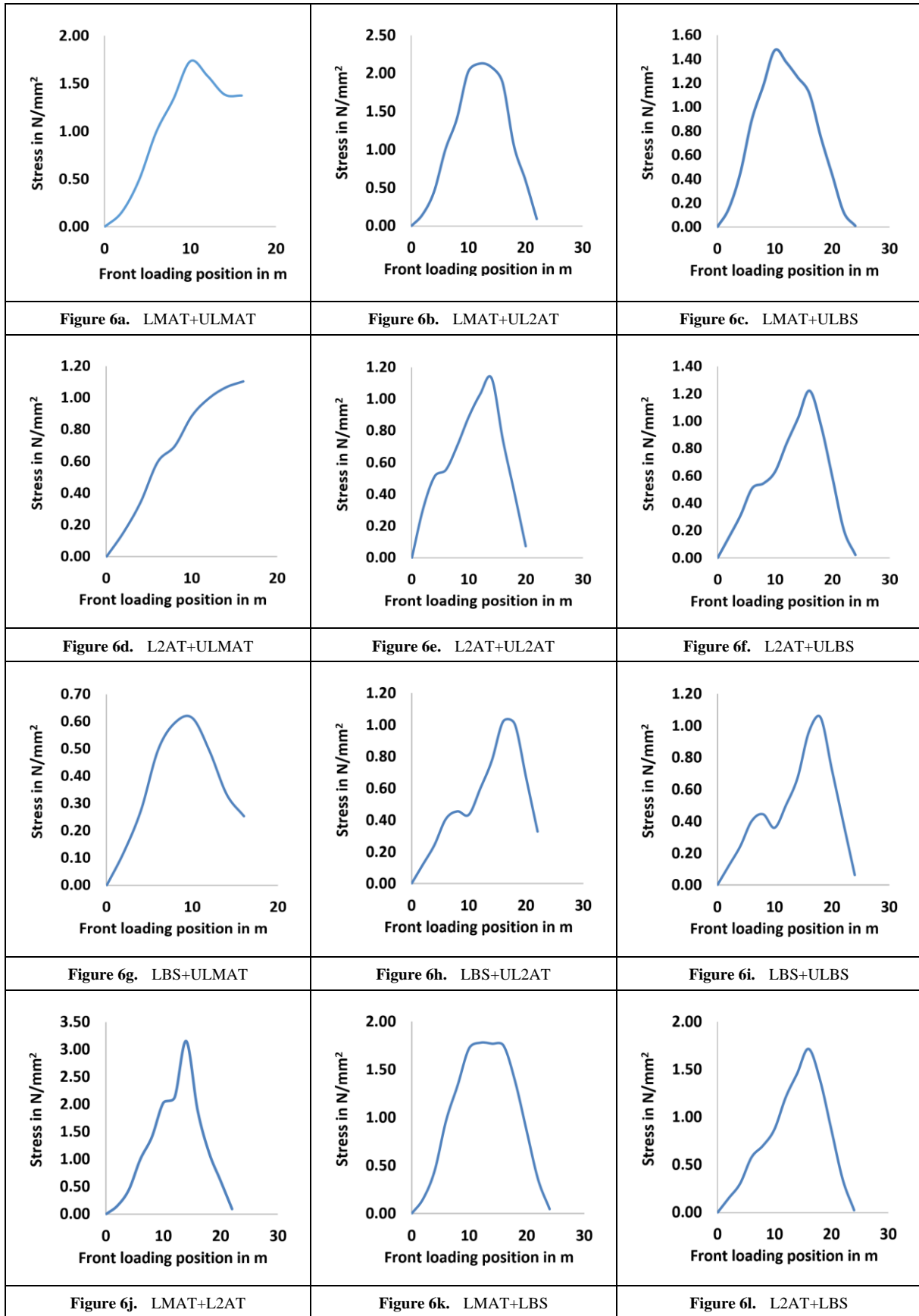


Figure 5. Variation in stress for the bridge studied on single moving vehicles case



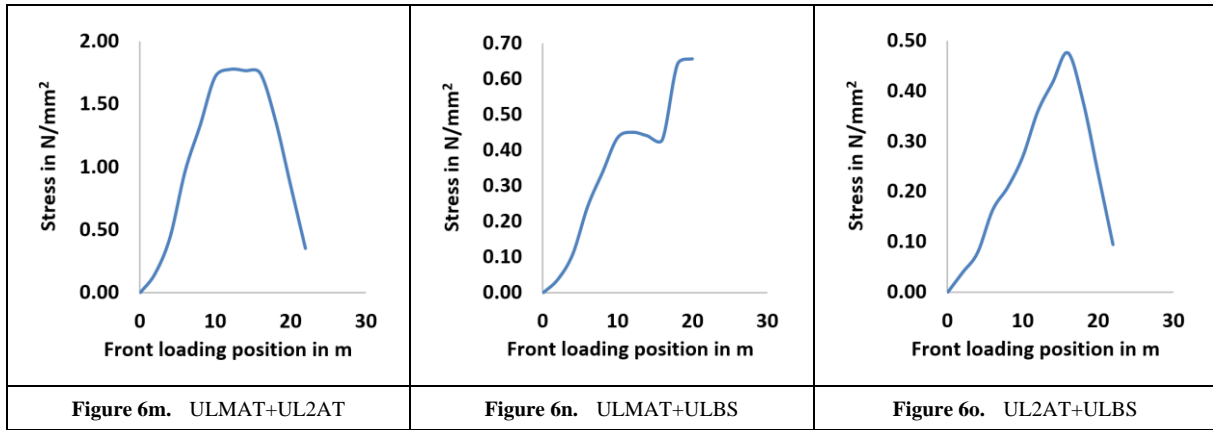
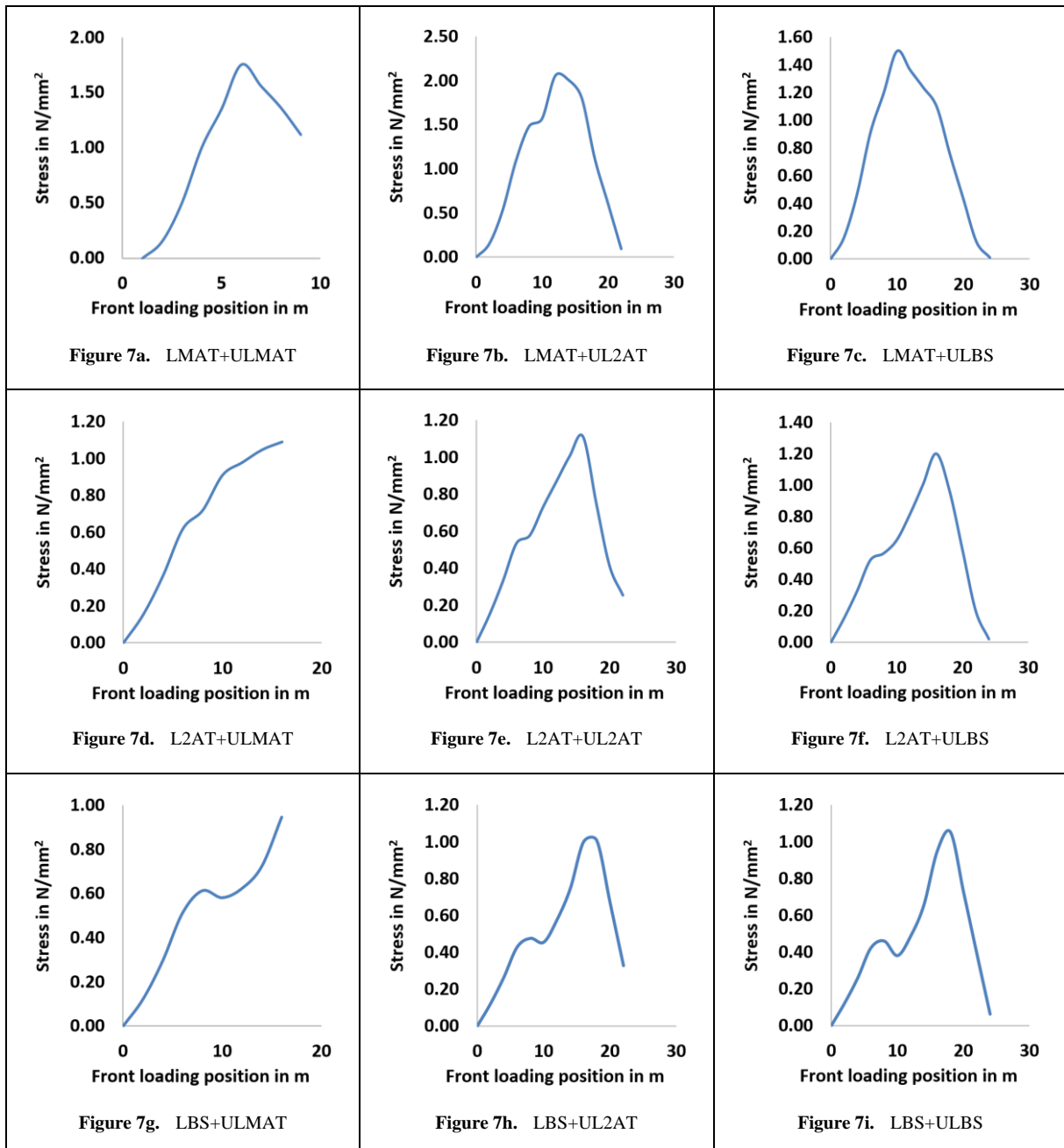


Figure 6. Stress variation of thze bridge combinations of fast moving vehicles



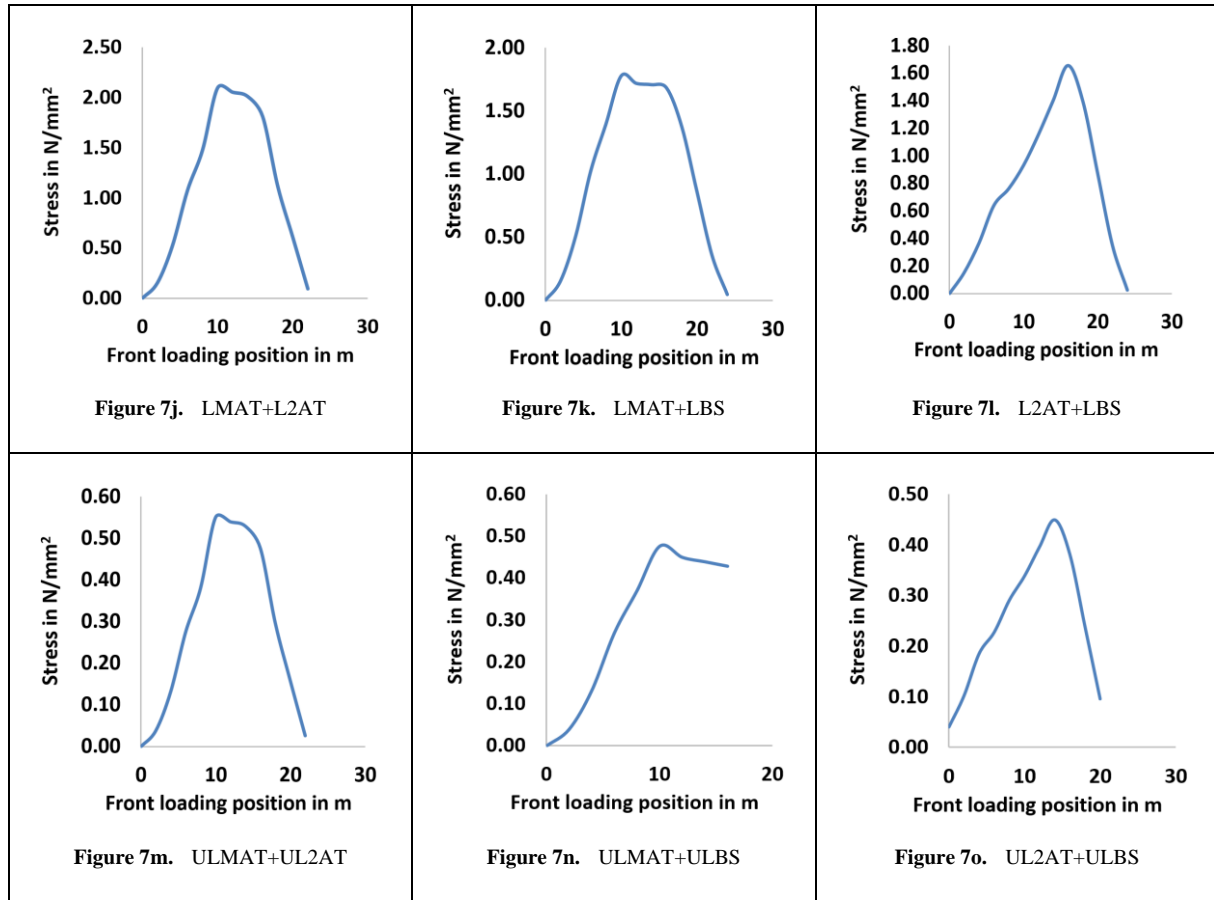


Figure 7. Stress variation of the bridge combinations of slow moving vehicles

3.2. Equivalent Effect of Moving Loads by Cycles Counting Method

The equivalent effect of moving loads is calculated using the stress ranges and the number of cycles as presented in the Figs 5, 6, and 7. For each scenario of moving vehicles (single vehicle, Fast moving and slow moving), the analysis results of moving loads are utilized to determine the maximum stress range ($S_{r_{max}}$) and the corresponding number of cycles. The equivalent number of stress range cycles (N_{eq}) is calculated by comparing each stress range to the maximum stress range within the same spectrum, as described in the Equation (3). The outcomes of this analysis are summarized in the Tables 5, 6 and 7.

3.3. Equivalent Static Stress Range

The rain flow approach is used to calculate the stress ranges for each load category based on the complex stress history with data analysis determining the frequency of each category. The stress ranges acting on the structure during one year period are then compiled and analyzed for frequency, with the number of intervals computed using Sturge's formula. Equation (4) calculates the equivalent static stress (S_{es}), with a focus on the vehicles that cause the most stress. Since the analysis comprises three types of

movement of vehicles, the algorithm ends after considering operations of all three vehicles. Tables 9, 10 and 11 are the equivalent stress range of the bridge for all types of moving vehicles with and without combination and Table 12 presents the equivalent stress range of the bridge considering traffic data for the last 5 years.

3.4. Reliability Index

The reliability indexes for varying desired number of cycles (N_s) obtained from different case studies are given below:

Case Study 1: The Bridge that is newly built has an initial crack of size 0.00041m according to ACI 224R-01, ACI committee.

- 1a- Bridge subjected to fast moving vehicles.
- 1b- Bridge subjected to slow moving vehicles.
- 1c- Bridge subjected to single moving vehicle.

Case Study 2: The Bridge that has been considered for study. It was assumed that the bridge was subjected to the current traffic volume for the previous 9 years. Further for that bridge having an initial crack size of 0.00041m, for the number of cycles which it has undergone in 9 years for the different types of moving vehicles, the current crack size is computed.

- 2a- Bridge with current crack size 0.00049m subjected to fast moving vehicles.
- 2b- Bridge with current crack size 0.00054m subjected to slow moving vehicles.
- 2c- Bridge with current crack size 0.00073m subjected to single moving vehicle.

Case Study 3: It is like case study 2, but with a traffic growth of 5% every year.

- 3a- Bridge with current crack size 0.000482m subjected to fast moving vehicles.
- 3b - Bridge with current crack size 0.00052m subjected to slow moving vehicles.
- 3c- Bridge with current crack size 0.00068m subjected to single moving vehicles.

The values of the reliability index computed for evaluation and design are presented in the Table 8. Also, to calculate the inherent safety level (in terms of reliability index) in different types of bridges, reliability analysis is carried out as illustrated in the Fig 8.

From the results obtained in the Fig 8, for the case study 1, it is seen that values of β range from 2.517 to 1.858 (case study 1a), 2.517 to 1.858 (case study 1b), and 3.306 to 1.342 (case study 1c) respectively. Similarly, for case study 2, values of β range from 2.16 to 1.762 (case study 2a), 2.043 to 1.727 (case study 2b), and 2.209 to 1.827 (case study 2c) respectively. For case study 3, β ranges from 2.204 to 1.776 (case study 3a), 2.083 to 1.74 (case study 3b), and 2.333 to 1.036 (case study 3c) respectively. Thus, we confirm with the reliability analysis.

Table 5. Equivalent Effect of Moving Loads for the Bridge Considered for the Study of Combination of Fast Moving

Sl. No	Vehicle combinations	$S_{r_{max}}$ (MPa)	N (cycles)
1	LMAT + ULMAT	1.73	1.02
2	LMAT + UL2AT	2.13	1.009
3	LMAT + ULBS	1.476	1.028
4	L2AT + ULMAT	1.106	1.031
5	L2AT + UL2AT	1.132	1.06
6	ULBS + L2AT	1.22	1.01
7	LBS + ULMAT	1.83	1.03
8	LBS + UL2AT	1.476	1.23
9	LBS+ULBS	1.326	1.014
10	LMAT + L2AT	3.153	1.013
11	LMAT + LBS	2.23	1.002
12	LBS + L2AT	1.89	1.009
13	ULMAT + UL2AT	0.488	1.088
14	ULMAT + ULBS	0.47	1.013
15	ULBS + UL2AT	0.46	1.1213

Table 6. Equivalent Effect of Moving Loads for the Bridge Considered for the Study of Vehicles Single Vehicle moving Case

Sl. No	Vehicle	$S_{r_{max}}$ (Mpa)	N(cycles)
1	LBS	0.825	1.033
2	ULBS	0.32	1.32
3	L2AT	0.845	1.05
4	UL2AT	0.28	1.05
5	LMAT	1.291	1.029
6	ULMAT	0.399	1.28

Table 7. Equivalent Effect of Moving Loads for the Bridge Considered for the Study of Combination of Slow Moving Vehicles

Sl. No	Vehicle combinations	Sr _{max} (MPa)	N(cycles)
1	LMAT + ULMAT	1.756	1.028
2	LMAT + UL2AT	2.058	1.026
3	LMAT + ULBS	1.497	1.036
4	L2AT + ULMAT	1.097	1.045
5	L2AT + UL2AT	1.111	1.014
6	ULBS + L2AT	1.201	1.006
7	LBS + ULMAT	1.32	1.119
8	LBS + UL2AT	1.001	1.037
9	LBS+ULBS	1.053	1.052
10	LMAT + L2AT	2.050	1.016
11	LMAT + LBS	1.988	1.008
12	LBS + L2AT	1.77	1.010
13	ULMAT + UL2AT	0.488	1.091
14	ULMAT + ULBS	0.455	1.183
15	ULBS + UL2AT	0.568	1.123

Table 8. Reliability Index for various desired number of cycles

Reliability index (β) for various case studies									
N _s	1a	1b	1c	2a	2b	2c	3a	3b	3c
2×10 ⁶	2.517	2.517	3.306	2.16	2.043	2.209	2.204	2.083	2.333
2×10 ⁷	2.501	2.501	2.412	2.146	2.033	2.201	2.184	2.073	2.32
2×10 ⁸	2.29	2.29	1.697	2.028	1.943	2.102	2.063	1.975	2.205
2×10 ⁹	1.858	1.858	1.342	1.762	1.727	1.827	1.776	1.74	1.868
2×10 ¹⁰	-	-	-	-	-	-	-	-	1.036

Table 9. Equivalent stress range of the bridge for slow moving vehicle combination

Sl No	Slow moving vehicle combination	Cycles (n)	No of Vehicles (X)	Relative frequency (Pi)	Cycles for 1 year (n*X*365)	Stress range (f)	[Pi*(f) ^m]
1	LMAT+L2AT	1.016	420	0.2620	155753	2.05	4.63
2	LMAT+LBS	1.088	705	0.4398	279970	1.77	4.32
3	LMAT+UL2AT	1.028	478	0.2982	179355	2.058	5.35
			1603				16.52
Equivalent Stress Range = (16.52)^(1/4) = 2.01N/mm²							

Table 10. Equivalent stress range of the bridge for fast moving vehicle combination

Sl No	Fast moving vehicle combination	Cycles (n)	No of Vehicles (X)	Relative frequency (Pi)	Cycles for 1 year (n*X*365)	Stress range (f)	[Pi*(f) ^m]
1	LMAT+L2AT	1.023	289	0.15967	107911	3.153	15.78
2	LMAT+LBS	1.002	551	0.30442	201517	1.89	3.88
3	LMAT+UL2AT	1.009	970	0.53591	357236	2.13	11.03
			1810				30.69
Equivalent Stress Range = (30.69)^(1/4) = 2.35N/mm²							

Table 11. Equivalent stress range of the bridge for single moving vehicle

SI No	Single moving vehicle	Cycles (n)	No of Vehicles (X)	Relative frequency (Pi)	Cycles for 1 year (n*X*365)	Stress range (f)	[Pi*(f) ^m]
1	LBS	1.022	840	0.3259604	313345.2	0.825	0.15
2	L2AT	1.058	1259	0.4885525	486188.03	0.846	0.25
3	LMAT	1.026	478	0.185487	179006.22	1.291	0.51
Equivalent Stress Range = (0.91)^(1/4) = 0.97N/mm²							

Table 12. Equivalent stress range of the bridge considering traffic data for the last 5 years

SI No	Vehicle combinations	Year 2018	Year 2019	Year 2020	Year 2021	Year 2022
1	Fast Moving	2.74	2.46	2.53	2.46	2.55
2	Slow Moving	2.02	2.2	2.12	2.06	2.05
3	Single vehicle	1.175	1.105	1.165	1.24	1.149

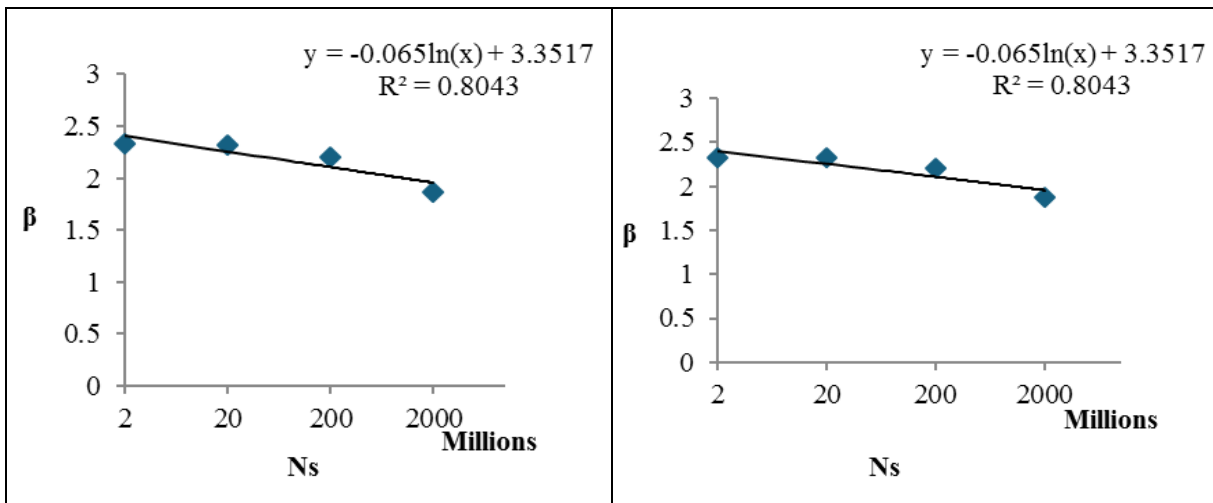


Figure 8a. β versus log Ns for case study 1a

Figure 8b. β versus log Ns for case study 1b

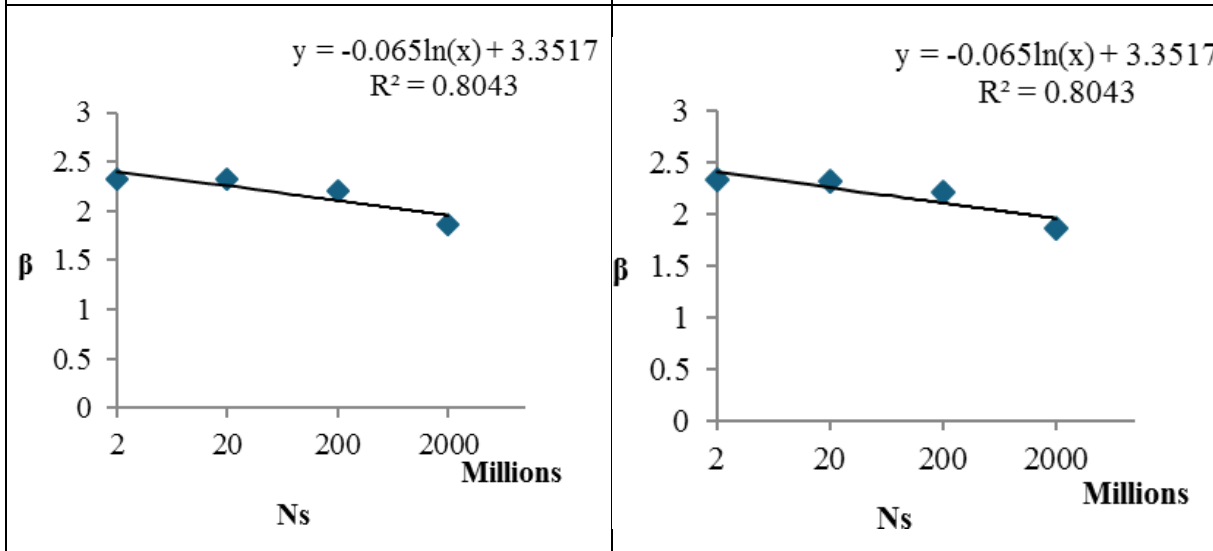


Figure 8c. β versus log Ns for case study 1c

Figure 8d. β versus log Ns for case study 2a

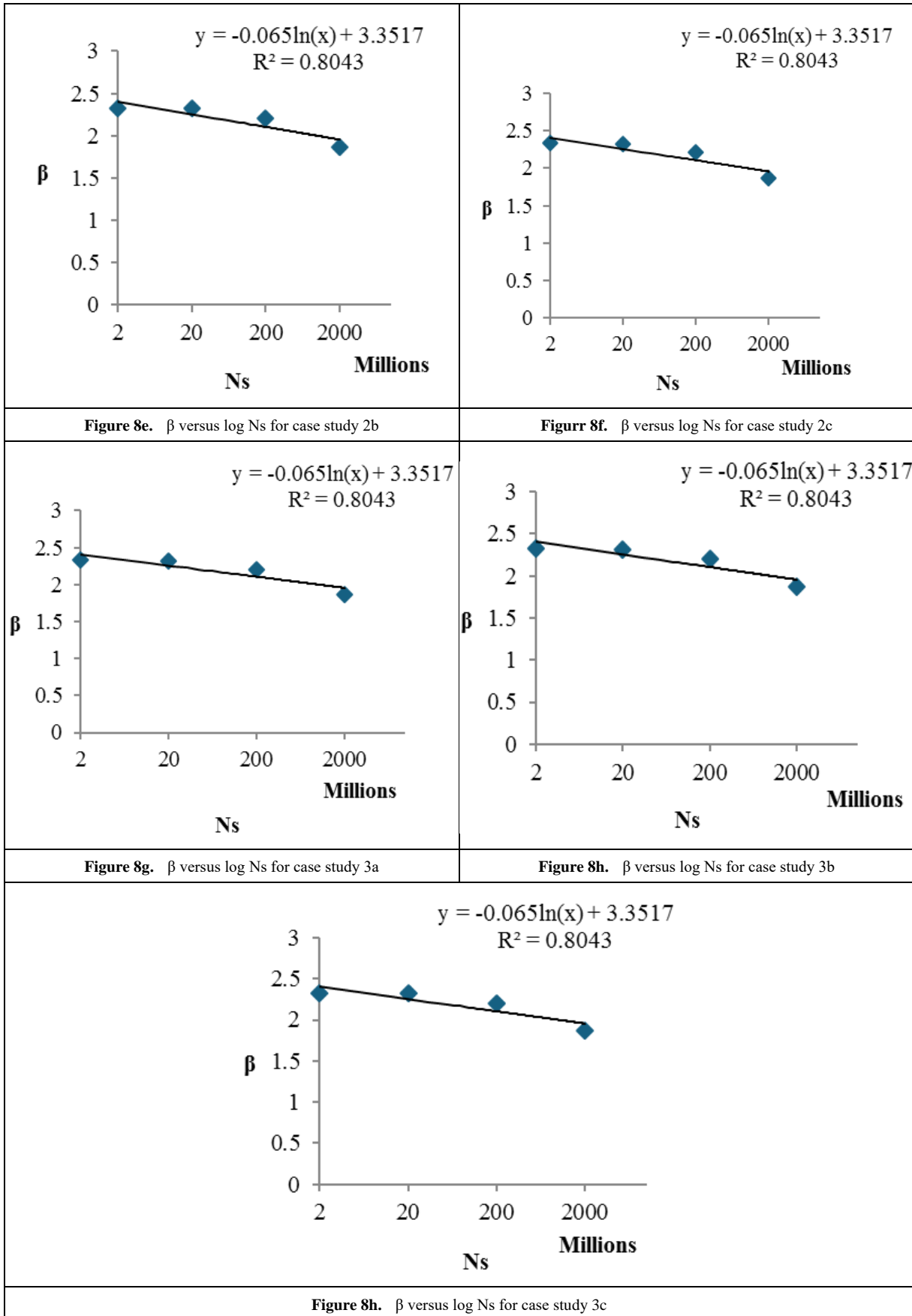


Figure 8. Regression analysis of the reliability index for various case study

4. Conclusions

Reliability index β is also calculated for the reinforced concrete bridge at actual equivalent stress range. An important parameter to be considered in fatigue analysis of bridges is Equivalent Stress range (Ses) and detected crack size (ad). From the results obtained, it can be concluded that

1. In all case studies, the value of the Reliability index (β) is observed to be decreased with an eventual increase in the number of cycles.
2. For Ns of 2×10^6 , the β value is found to be higher at scenario 3 i.e., $\beta=3.306(1C)$, $2.209(2C)$, $2.333(3C)$, $3.023(4C)$. This is because the stress developed due to the single moving vehicle is less.
3. Reliability regression analysis thus done is useful in arriving at inherent β levels for different numbers of cycles and also to arrive at an optimal inspection interval.
4. Reliability index (β) for the bridge with initial crack of size 0.00041m is 2.517 and 2.517 for 2×10^6 desired number of cycles for fast and slow moving vehicles, 306 for 2×10^6 desired number of cycles for single moving vehicles.
5. Reliability index (β) for the bridge with no traffic growth for 9 years having detected cracks of size 0.00049m, 0.00054m, and 0.00073m is 2.16, 2.043, and 2.209 for 2×10^6 desired number of cycles for fast moving, slow moving and single moving vehicles respectively.
6. Reliability index (β) for the bridge with 5% traffic growth for 9 years having detected cracks of size 0.000482m, 0.00052m, and 0.000682m is 2.204, 2.083 and 2.333 for 2×10^6 desired number of cycles for fast moving, slow moving and single moving vehicles respectively.

Abbreviations

LEFM - Linear Elastic Fracture Mechanics
 RCC - Reinforced Cement Concrete
 LHS - Latin Hypercube Sampling

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