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Non-Linear Damage Accumulation based Fatigue Life Estimation of Reinforced Concrete Bridges

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Abstract
This paper presents an attempt to determine fatigue life of reinforced concrete bridges by adopting a non-linear damage accumulation method subjected to different amplitude loading due to passing of vehicles in Nepal. The bridge was modeled in finite element software and static analysis was carried out to determine the stresses acting on a bridge deck. The corresponding stresses in reinforcement bars is determined using limit state method and the stresses are incorporated in sequential law to carry out the fatigue life. Since S-N curves available in different codes represents stresses corresponding to more than hundred thousand cycles of failure, a full range S-N curve is developed to carry out sequential law. The material properties of the modeled bridges are taken from design data. The paper concludes that the fatigue damage due to sequential law is low in previous years; however, there is exponential increase in damage in later years. Although the updated linear method seems to yield almost comparable result as sequential law, the fatigue progress is best represented by sequential law.

Keywords
Sequential Law, reinforced concrete bridge, S-N curve, Fatigue damage, Non-linear damage

1. Introduction

Transportation infrastructure such as bridges are subjected to repeated cyclic loads throughout their lives that cause fatigue in its structural components. Fatigue, as defined, is the progressive and localized structural change that occurs due to repeated cyclic loading. Due to continuous repetition of loads fatigue distress occurs and materials like steel and concrete undergo brittle failure much before their yield and ultimate strength are reached. Thus, the nature of loading in bridges can be taken as the major indicator of its performance in fatigue.

In an reinforced concrete bridges,deck slabs, which are found to be most critical elements for fatigue failure, undergo millions of large load cycles during its service life [1].Despite these facts, the prevailing design codes do not consider the effect of fatigue in the design of RC bridge deck slabs.Therefore, research needs to be carried out to determine the service life of RC bridge decks considering fatigue environment.

The load acting on a bridge is variable in nature.Different vehicle with different axle weights have different stress impacts on the bridge. There have been many studies related to the interaction of lower and higher stress levels in fatigue life estimation.Linear damage accumulation rule recommended by most of the design codes may over-estimate or under estimate fatigue damage in the bridge because it does not consider the loading sequence effect. The fatigue performance of the bridges is different than what Miner's rule estimates. In order to incorporate the load sequence effect, a new damage indicator based sequential law as proposed by Mesmacque et.al [2] is useful to estimate the fatigue life of the RCC bridge.

In a reinforced concrete T-girder bridge, there are basically two failure modes: Concrete failure mode and reinforcement bars failure mode. Various experiments were carried out to find out the dominant fatigue failure mode.Barnes & Mays,[3] conducted fatigue tests on five RC girders and showed the dominant one is fatigue fracture in tensile reinforcements.Heffernan & Erki [4] in their experimental study on twelve girders found out that the specimens failed as a result of brittle fracture of tensile rebars and they succeeded in increasing fatigue life by using carbon fiber plate (CFRP) due to lowering of stresses in rebars.However their experimental results were based on small-scale specimen.Charalambidi et.al[5] studied fatigue behavior of large scale reinforced concrete girders and their test results have shown that girders, even being large sized,primarily failed due to tensile fracture of steel rebars. This concludes that the dominant fatigue failure mode of RC bridge girder is tensile fracture of steel rebar and is irrespective of the size of test specimen.

Habeeba et.al[6] used a non-linear finite element and the S-N curve to evaluate the fatigue of an RCC bridge. Field strain measurements were used by Alampalli & Lund[7] and Zhou [8] to determine fatigue life.Many alternative ways are defined, but AASHTO defines the core approach. The S-N curve is commonly used to estimate fatigue life, and many researchers have followed suit, determining the failure number of cycles by locating matching stresses operating on the bridge component.

Bridges must bear fluctuating loads throughout the course of their lives, but because calculating this type of load is difficult, these loads are transformed to comparable constant loads using the rain flow counting method. Damage accumulation is also done using Miner's rule, which is a linear damage accumulation rule. However,Siriwardane et.al [9] and Dattoma et.al[10] discovered that utilizing Miner's rule for variable amplitude loading, life estimates were shown to be incorrect since it does not account for load sequence effects. As a result, novel damage accumulation algorithms that account for non-linearity and load sequence impact have been devised. For variable amplitude loading Mesmasque et.al[2] suggested a new damage indicator-based fatigue sequential law. By providing a new damage parameter, damage-induced tension is carried from one level to the next until the ultimate stress is reached.Thus, the results obtained using the sequence effect are more realistic than the linear damage accumulation rule, according to the above-mentioned new damage models.

2. Theory Background and Methodology

2.1 Non-Linear Damage Indicator

The Linear Damage accumulation model does not take into account the loading history as a result of which, for the same loading condition the Miner's rule and experimental results differs to a great extent. A new damage indicator based sequential law is used to obtain a realistic fatigue life for bridges. The main principle on which this law is based is that if the physical state of damage is the same, the fatigue life depends only on loading condition.

Suppose a part of component is subjected to certain stress range of σ_{i} failure number of cycles which is obtained from the S-N curve of corresponding component. Hence the residual life at level i can be obtained as (Ni-ni). A new damage stress $\sigma_{1\mathrm{eq}}$ is obtained from S-N curve corresponding to failure cycle (Ni-ni). Here, the damage stress is stress corresponding to remaining life. Now a new damage parameter $\mathrm{D_i}$ is introduced, defined as the ratio of increment of damage stress and difference between ultimate and applied stress. The damage indicator is normalized to 1 at failure.

$$D(i) = \frac{\sigma(1)eq - \sigma i}{\sigma u - \sigma i} \tag{1}$$

Where, $\sigma_{1\mathrm{eq}}$= damage stress; σ_{i}= applied stress; σ_{u}= ultimate stress of material At first cycle, $\sigma_{\mathrm{edi}} = \sigma_{\mathrm{i}}$ hence $\mathrm{D_i}$=0 and as no of stress cycles increases, the damage approaches to 1. The damage is then transferred to next level i+1 by following relation

$$D(1) = D'(i) = \frac{\sigma(1)eq - \sigma i}{\sigma u - \sigma i} = \frac{\sigma'(1)eq - \sigma(i+1)}{\sigma u - \sigma(i+1)} \tag{2}$$

Where $\sigma'_{(1)\mathrm{eq}}$ = damage equivalent stress at level i+1; $\sigma_{\mathrm{i+1}}$ = applied stress at level i+1 We then calculate $\sigma'_{(1)\mathrm{eq}}$ and corresponding failure of cycle $\mathrm{N'_{(1)R}}$ at level i+1 Now for next step; applied stress range is σ_2, and corresponding applied number of cycles is $\mathrm{n_2}$, residual failure number of cycles is determined as $\mathrm{N_{2R}}$= $\mathrm{N'_{1R}}$- $\mathrm{n_2}$. For $\mathrm{N_{2R}}$, corresponding new damage stress $\sigma_{2\mathrm{eq}}$ is determined and damage is again calculated as

$$D(i) = \frac{\sigma(2)eq - \sigma 2}{\sigma u - \sigma 2} \tag{3}$$

In the same way the damage is again transferred to next step and same process is carried out until damage is equal to unity.

2.2 S-N curve

An empirical relationship for fatigue stress and failure number of cycles was proposed by Swiss Society of Engineers and Architects (SSEA) and using the same the S-N curve of reinforcement bars has been derived [11]. The relationship is given as

$$\Delta\sigma = \left(\frac{A}{N}\right)^{1/K} \tag{4}$$

Where $\Delta\sigma$=stress range;A=fatigue detail coefficient of steel bar;N=no of fatigue stress cycles;K=constant value of the slope of the S-N line

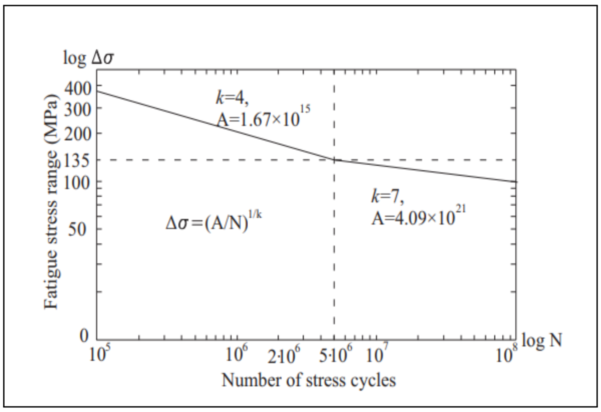

Figure 1: S-N curve of reinforcement bar

2.3 Full Range S-N curve

Code provided S-N curve represents stresses corresponding to more than hundred thousand cycles of failure. However, in the case of sequential law it is essential to use full range number of cycles in S-N curve. So, the partially known S-N curve is to be developed in full range S-N curve using Kohout and Vechet modelling technique

Initially, the known partial S-N curve is plotted in log-log graph. Then the three important straight lines is drawn. First horizontal line is drawn across the ultimate strength for the low cycle region where $\sigma=\sigma_u$. A second horizontal line is drawn across the endurance limit for high cycle region where $\sigma=\sigma_\infty$. Third, a tangent as described by equation of partial known curve is drawn for the region of finite life. The point of intersection of third line with first and second horizontal line projects to give value of B and C along x-axis.

The equation of full range curve is written in the form:

$$\sigma = \sigma_\infty \left(\frac{N+B}{N+C}\right)^{b} \tag{5}$$

where b is the slope of tangent in the region of finite life.

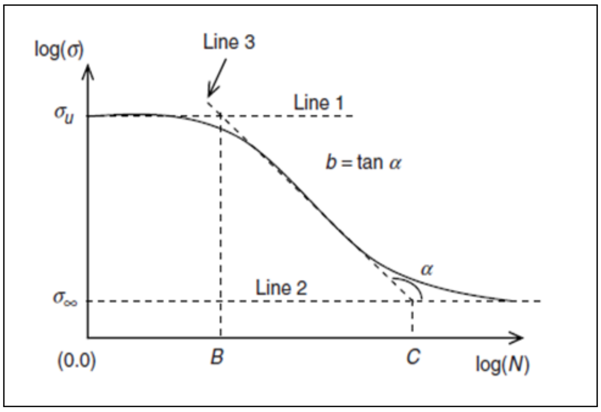

Figure 2: Graphical representation of full range S-N curve using Kohout and Vechet Modeling technique

2.4 Stress Range

From finite element method, stress in top compression fiber of concrete is determined. The stress in top compression fiber of concrete is converted to equivalent stress in reinforcement bars by using limit state method. The maximum moments in normal section of bridge deck is determined considering the equilibrium of internal forces on failure plane. A triangular stress diagram is assumed.

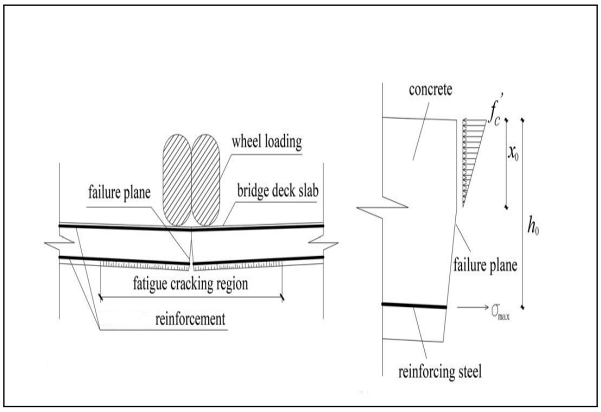

Figure 3: a) Failure mode of reinforcement bar b) Stress distribution on failure plane

2.5 Bridge description

The bridge sample selected is Dash Khola Bridge of Eastern Nepal spanning 75.6m with three spans each of 25 m. It has a carriage way width of 6m and total deck width of 7.2m.It is a simply supported RCC T-Girder bridge. Two intermediate reinforced concrete circular pier divides the span in to three equal division. The cross section of the deck slab is shown in Figure

4 .

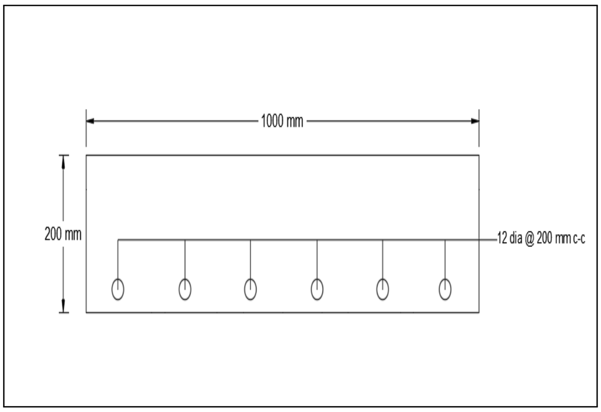

Figure 4: Bridge deck section

2.6 Finite Element Modeling

The bridge deck was analyzed using the finite element method (FEM) with the aid of available software CSI Bridge v.20. User defined vehicles with vehicle configuration as explained in table 1 is used in this study and static analysis is carried out and the stress variation with time step is plotted for each vehicle selected and hence a stress history plot for top fiber of concrete is obtained. A three-dimensional model of full bridge was analyzed under different class vehicles and the results were compared with that of bridge used in Pokhrel(2013)[12]. From the results it was seen that the results of bending moment and shear force were in good agreement. Therefore, the considered model was defined as a ”validated analytical model”.

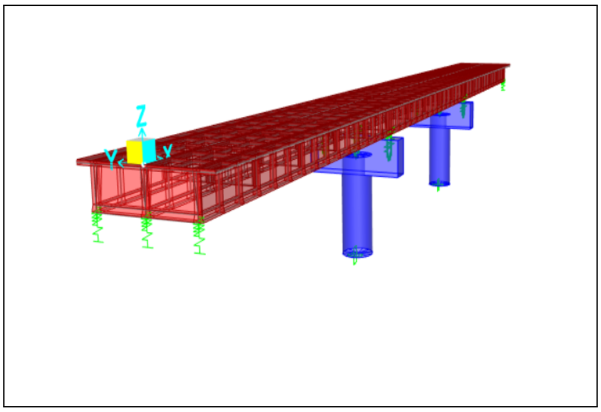

Figure 5: Global Finite Element Model of Bridge

2.7 Remaining fatigue life estimation based on primary stresses

To incorporate sequential law, primary stress ranges generated by the passing of vehicles over the bridge are determined. Since uniform distribution of stress is assumed along the reinforcement bars, the stress history for present vehicle traffic is obtained. It was assumed that the traffic sequence is almost constant during single day. Then the validated model is used to determine stress history of concrete and converted to equivalent stresses in reinforcement bars. Although dynamic effect of moving vehicles has some impact on fatigue life, it is ignored during the study. The stress history was converted to stress range using limit state method of RC bridge deck failure. As stated earlier, the tensile steel fatigue fracture occurred first and hence the limit state is controlled by steel fracture. So the fatigue life considered steel failure shows a safer approach for fatigue life estimation rather than concrete fatigue failure.

The type of vehicles used for study are tabulated below in table 1

3. Results

Analysis of real vehicles generally run in Nepal ie. LPK 1613, LPK 2518 and LPO 1618 were carried out on CSI Bridge v 20 software and corresponding stresses were determined and their sequential effect were incorporated in fatigue life.

Updated S-N curve

The equation for full range S-N curve has been derived using Kohout and Vechet Modelling Technique.

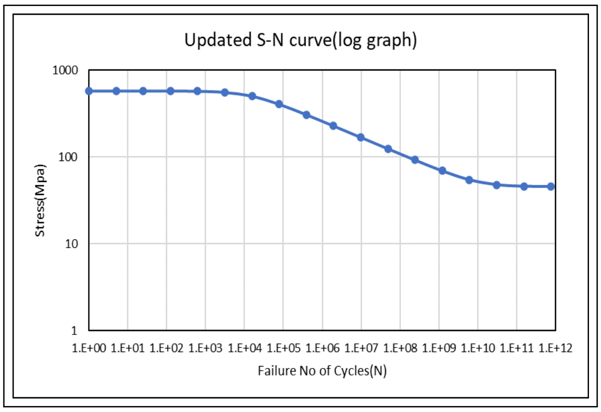

Figure 6: Full range S-N curve for reinforcing bars

3.1 Stress History of Different Vehicles

Finite element modeling is used to determine the stresses in the top fiber of concrete. Stresses in reinforcing bars, on the other hand, cannot be derived from 3-d structural modeling in macro modeling

Table 1: Vehicle configuration

Vehicle Type	Bus (BS)	Single axle truck	Multi Axle Truck
Vehicle Name	LPO1618	LPK1613	LPK2518
Wheel base	6.3 m	3.58 m	3.88 & 4.88 m
Total length of vehicle	12 m	6.365 m	7.08 m
Width of vehicle	2.6 m	2.115 m	2.44 m
Max permissible FAW	54 KN	60 KN	60 KN
Max permissible RAW	108 KN	102 KN	190 KN

software. As a result, the stresses of reinforcement bars are calculated using the limit state method.The variation of stresses with time in top fiber of concrete is determined from finite element software and for each time step, the stress in rebar is calculated using limit state and hence a stress history plot is obtained for reinforcement bar.For each vehicle, similar graphs are obtained and stress range is obtained for different considered vehicle.The stress range obtained from the graphs are incorporated in sequential law to determine fatigue damage.The variation of stresses in bridge deck reinforcement bars over time for various vehicles is plotted in figures 7,8 and 9

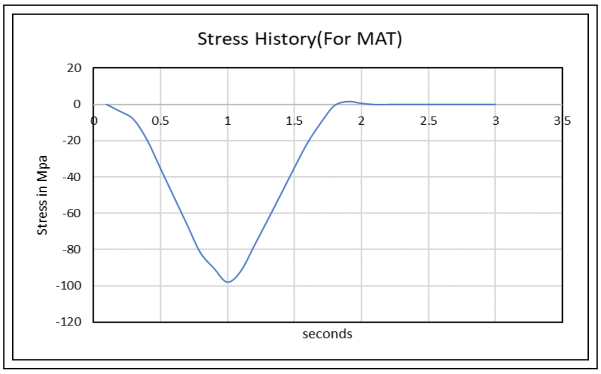

Figure 7: Stress history of MAT

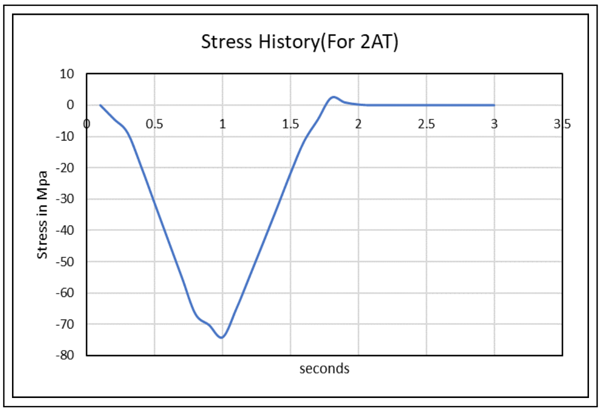

Figure 8: Stress history of single axle truck

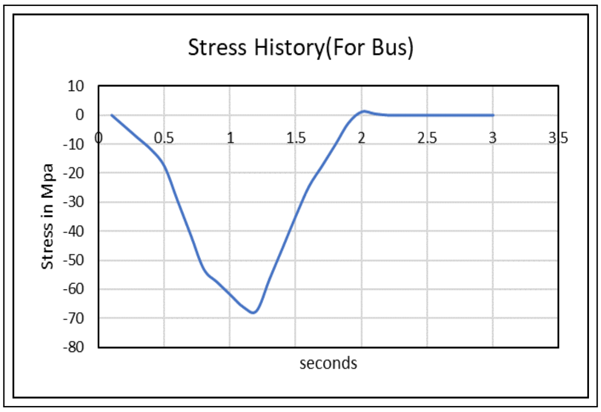

Figure 9: Stress history of bus

3.2 Fatigue life analysis

The new damage indicator was calculated from the date of bridge construction to present by considering the sequence of stress ranges of reinforcement bars. The time required for the new damage indicator (Di) to be equal to 1 is considered as fatigue failure. Because the fatigue life is controlled by tensile steel fatigue fracture is shorter than that controlled by compressive concrete fatigue failure, the fatigue life analysis is done based on damage on reinforcement bars which shows a safer approach for fatigue life estimation. The damage by linear method is again carried out using updated S-N curve where damage d_i is given by n_i/Ni. The calculated fatigue life for different approaches are tabulated in table 2.

Table 2: Fatigue life in years

	Fatigue Life
Sequential Law	113
Miner's rule	91
Updated Linear Method	118

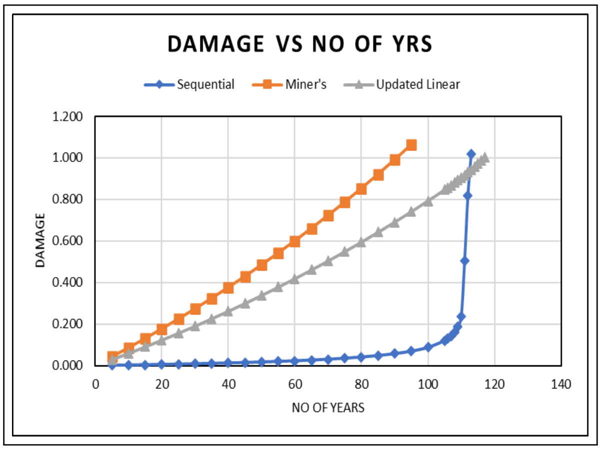

Figure 10: Damage vs Fatigue Life

4. Discussion of Results

The steepness in graph in damage of sequential law demonstrates that the damage is comparatively very high in later years than the early years. As fracture mechanics explains, for the first few years, the initiation of cracks in rebar does not occur. Once the crack initiates, the propagation of crack is rapid and the damage is exponential and the result shows the same. As stated earlier, the damage by Miner's rule is almost linear. Comparison results shows almost 22 years variation in fatigue life in no overloading condition for sequential law and Miner's law approach. Updated linear method where the damage is ratio of cycles acted to failure number of cycles from updated S-N curve is almost comparable to sequential law approach however, the fatigue progress is best represented by sequential law.

5. Conclusion

In this paper, the fatigue life of RCC T-Girder bridge is calculated by incorporating the sequential effect which appears due to loading of different amplitudes on bridges. For different vehicles, the stress time history is obtained at bridge deck. The concrete stress is converted to equivalent stress at reinforcement bars using limit state and sequential law is applied to carry out the fatigue damage. The fatigue damage due to Linear Damage Accumulation Rule (Miner's Rule) is also calculated and compared. From the results obtained, it can be concluded that

1. The damage due to sequential law is comparatively low in first 100 years however there is exponential increase in damage in following few years.

2. The estimated fatigue life using sequential law is high as compared to Miner's damage so the result by linear rule is conservative.

3. More comparable experimental and sequential law damage results show the validity of new damage indicator based sequential law hence sequential law is advised for fatigue life estimation of bridges. Although the updated linear method seems to yield almost comparable result as sequential law, the fatigue progress is best represented by sequential law.

6. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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