Fatigue Life Estimation of an Integral RC Bridge Subjected to Transient Loading Using Ansys

M. Verma and S. S. Mishra

Abstract Integral bridges are becoming popular day by day, as they are easy to construct and require lesser maintenance efforts due to absence of bearings. There is an increasing tendency to construct long-span bridges. However, due to movement restraints, fatigue stresses build-up that leads to a reduction in the useful life. In this study, an effort has been made to estimate the fatigue life of an integral bridge subjected to transient loads. In this paper, the results of transient analysis of an integral bridge of total length 156 m having five continuous spans with a maximum span of 40 m has been done using ANSYS. The roles of deformation and von-Misses stress that occur in the bridge have been found to influence fatigue life. Further, midpoint deflection in the longest span, its variation with loading history, and its influence on fatigue life have been analyzed and found to match satisfactorily with standard results, and the same process is applied on various length of a longer span.

Keywords Integral bridge · Fatigue life · Transient loading · ANSYS

1 Introduction

Integral bridges in the simplest term can be classified as bridges that are constructed without joints between pier and deck. In Integral bridges, the monolithic connection is established between the superstructure (deck and girder) and the substructure (piers and abutments). Starting from one abutment these bridges are constructed without joints to another abutment. They do not have any joints between other intermediate piers.

In Integral bridges, the bearings are removed to eliminate the problems associated with the installation, maintenance, and replacement of bearings, sometimes they are very costlier and become uneconomical to repair further, the jointless bridges that

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S. Dutta et al. (eds.), *Advances in Structural Vibration*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-15-5862-7_17

are used to avoid and eliminate the characteristic problems related with installing, maintaining, and repairing deck joints and bearings [11, 12].

Transient loading can be defined as loads and forces that occur and vary over a short time interval. A transient load can be to any load that will not remain on the bridge forever. Mostly, these loads include vehicular live loads and their tributary effects including dynamic load allowance, braking force, centrifugal force (caused in the curved section only), and live load surcharge. Additionally, there also exist pedestrian live loads, force effects due to uniform temperature, and gradient of temperature, force effects because of settlement of piers, river water force and pressure due to water stream on piers, wind loads on structure, wind on live load, friction forces that are generated between vehicle and deck pavement, ice loads in some areas, vehicular collision forces occur during accidents, vessel collision forces, and earthquake loads.

For most ordinary bridge case, there are a few transient loads which are likely to be considered and that are live loads of vehicle and their subsequent effects including braking force, centrifugal force, and dynamic load allowance. These subsequent effects shall always be collectively considered with the gravity effects of live loads. For this study, only the vehicular load is provided according to Indian-standard IRC-6:2014 and the permanent load that includes material load of bridge structural components and nonstructural components, load of material used in wearing coat of deck surfaces that is laid over deck are considered, for simplicity down drag forces, horizontal earth pressure loads, vertical pressure due to a dead load of earth fill [3], earth surcharge load, force effects due to creep, shrinkage, secondary forces that are generated from post-tensioning of members, and other forces that are introduced due to construction process are not taken into consideration.

Due to the above applied transient loading, the bridge deck deflects and expands and other parts of the bridge also show such tendency of deflection and expansion. This deflection and expansion from deck and girder are transferred to the piers because of fixity. The bridge girder in this transient case shows a behavior similar to a fixed beam [2]. As in the fixed beam, a large amount of deformation occurs at the mid-span and this deformation results in the plastic deformation of the beam [5]. A similar case will occur in the integral bridge, but under a different type of geometrical consideration like bridge length, span, or various other things are considered for later result verification. Depending upon these variations in expansion and deflection, the bridges may show different types of mechanical responses [1].

There are three methods of analyzing the fatigue life and these are strain life, stress life, and fracture mechanics [10]; In ANSYS 17.1 Fatigue Module, only strain life and stress life methods are available.

At present, the approach to strain life is commonly used. Strain life mainly deals with the occurrence of less number of fatigue cycle so-termed as low-cycle fatigue, by using this approach the fatigue life can be predicted to an acceptable limit. The strain life-based approach is based on crack initiation.

Whereas the stress life is depending upon the total life and has nothing to do with the crack initiation so it deals with the high number of cyclic loads before failure so it results in high cycle fatigue. Low-cycle fatigue refers to $<10^5$ cycles and high cycle fatigue refers more than this [7].

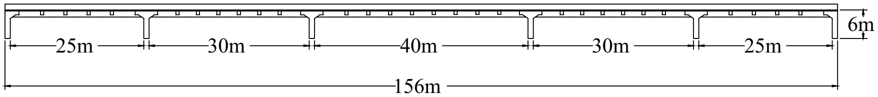

Fig. 1 A schematic diagram of the integral bridge

2 Steps for Fatigue Life Analysis Procedure

The study is required to be performed in a sequential manner to get the optimum results. There are following steps that are used:

1. Generating a Software-based Model using ANSYS 17.1 for fatigue analysis.
2. Applying the transient Loads using (IRC:6-2014 70-R).
3. Performing the analysis.
4. Validation of result obtained from Software with the mathematical approach.
5. Determine fatigue life of Integral Bridge.

The above procedure of analysis is repeated for the different span of bridge and different web thicknesses of girder are considered and analyzed further.

3 Modeling of Integral Bridge Under Study

For this study on an integral bridge similar to the existing Kalkaji Flyover at Okhla Industrial Area, New Delhi. Kalkaji Flyover is 150 m flyover that has been constructed at the vital T-junction on Ring Road near Kalkaji Temple is considered. It has typically five continuous spans of (25 + 30 + 40 + 30 + 25 m). It has a concrete slab deck of depth 1.70 m that is hunched and increased to 2.20 m at the piers. In this paper, soil properties are not considered and piles are assumed to be fixed (Figs. 1, 2 and Table 1).

4 Load Application

IRC:6-2014 recommendations are considered for load analysis. The total bridge width was taken as 8.25 m each of two lanes of 3.75 m each. A design load for 70R wheeled vehicle load as per IRC recommendation is used in this analysis. A large number of field investigations comprising such loadings of Integral abutment bridge [6]. The effect of live vehicle load is considered a positive impact on the fatigue life [4] of the bridge.

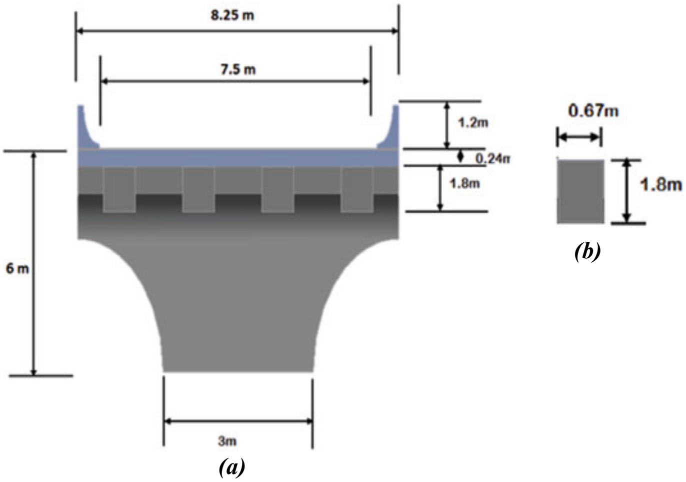

Fig. 2 **a** Various dimensions of the cross section of deck and pier. **b** Cross section of the longitudinal girder

Table 1 Material properties

S.N.	Material	Density (kg/m^3)	Modulus of elasticity (MPa)
1	Reinforced concrete	2500	50,000
2	Steel Fe415	7850	200,000

5 Development of the Numerical Model

To develop a finite element based mathematical model the physical design of the bridge is captured from and modeled in the software and material properties are assigned. The FEM model is able to capture every data that are required for the analysis. If fewer details are provided in the modeling, then the values are calculated in less number of iteration and results may be very approximate l the result may be verified with the experimental model (Fig. 3).

6 Analysis Procedure

For analyzing the fatigue performance of integral RC bridge, a vehicle of 100 t moves from one end to another in both lanes. These types of small bridges are usually constructed for city traffic so they travel between 40 and 60 km/h. with above speed consideration of 40 km/h.

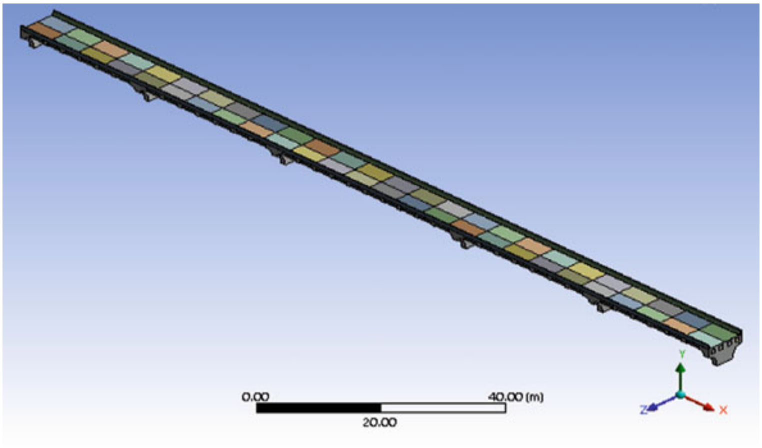

Fig. 3 Model of Kalkaji bridge in ANSYS 17.1

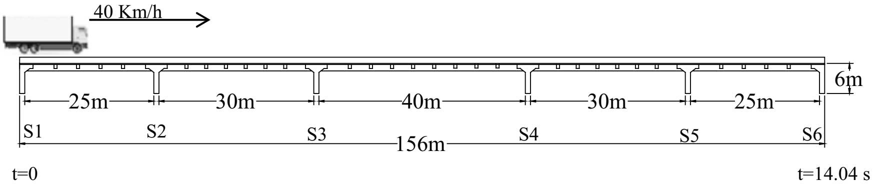

Fig. 4 Vehicle load and speed modeling

Figure 4 shows support S1, S2, S3, S4, S5, and S6, where maximum and minimum reaction force and moment reaction are extracted from ANSYS analysis result and further these results are used to find out the deformation and strain to calculate fatigue life bridge.

7 Force Reaction and Reaction Moment at Supports

Maximum, minimum, and resultant reactions are extracted from the model in each of six supports and the results are given in Tables 2 and 3.

8 Deformation

From the FEM model, Maximum deflection is occurring in the middle of the bridge as shown in Fig. 5 and maximum values occur in mid-position of the bridge.

Table 2 Force reactions extracted for modeling

Object name	Force reaction 1 (kN)	Force reaction 2 (kN)	Force reaction 3 (kN)	Force reaction 4 (kN)	Force reaction 5 (kN)	Force reaction 6 (kN)
Type	*Force reaction*					
Boundary condition	Fixed support S1	Fixed support S2	Fixed support S3	Fixed support S4	Fixed support S5	Fixed support S6
Results						
X-axis	−20.15	−39.34	−43.99	−54.99	−189.54	346.62
Y-axis	2.88	0.07	−0.54	−0.79	64.12	913.15
Z-axis	0.01	0	−0.03	0.25	−0.32	0.05
Total	20.36	39.34	43.99	55	200.1	976.72
Maximum value over time						
X-axis	208.35	1215.5	1440.7	1845.7	1396.5	1022
Y-axis	1524.6	1857.6	1898.7	1901.5	1863	1522.5
Z-axis	0.22	0.45	0.36	0.54	0.65	0.28
Total	1765.7	2018.2	2356.6	2374.6	2016.1	1759
Minimum value over time						
X-axis	−1044.7	−1408.9	−1828.7	−1442.8	−1234.1	−207.15
Y-axis	−101.37	−146.19	−73.42	−74.32	−145.66	−94.73
Z-axis	−0.31	−0.35	−0.44	−0.47	−0.57	−0.36
Total	3.47	7.26	5.13	11.49	0.59	0.54

Figure 6 represents the deformation that occurs in the bridge as vehicle approaches from one end to other; maximum deformation is found at the mid-span of value 6.25 mm for the bridge of 156 m. The maximum deformation increases for the bridge length of 161, 166, and 171 m as the bridge length increases.

9 Strain at Mid-Span of Longest Span

The calculated equivalent strain is plotted in Fig. 7 and the maximum value of the equivalent amplitude is 7.64×10^{-4} m/m or 0.764 mm, and it occurs at the mid-position of the bridge, where the span is maximum.

Table 3 Reaction moment extracted from analysis

Object name	Moment reaction 1 (kN m)	Moment reaction 2 (kN m)	Moment reaction 3 (kN m)	Moment reaction 4 (kN m)	Moment reaction 5 (kN m)	Moment reaction 6 (kN m)
Type	*Moment reaction*					
Boundary condition	Fixed support S1	Fixed support S2	Fixed support S3	Fixed support S4	Fixed support S5	Fixed support S6
Results						
X-axis	−0.15	0.16	−0.16	0.92	2.32	2.33
Y-axis	0.14	0.15	0.07	0.13	0.17	0.14
Z-axis	59.81	87.22	102.32	138.13	323.35	315.56
Total	59.81	87.22	102.32	138.13	323.36	315.57
Maximum value over time						
X-axis	1.02	7.22	10.65	4.95	4.65	7.2
Y-axis	5.82	3.16	8.95	1.75	0.73	0.6
Z-axis	1076	1493.4	1850.9	1548.1	1337.3	1634.33
Total	1076.1	1493.4	1851	1861	1477.7	1903.08
Minimum value over time						
X-axis	−9.62	−3.68	−7.26	−10.58	−7.56	−8.58
Y-axis	−2.33	−12.06	−1.35	−5.77	−6.64	−6.33
Z-axis	−451.05	−1351.4	−1550.5	−1861	−1477.7	−2107.2
Total	9.78	15	5.29	13.76	1.73	3.91

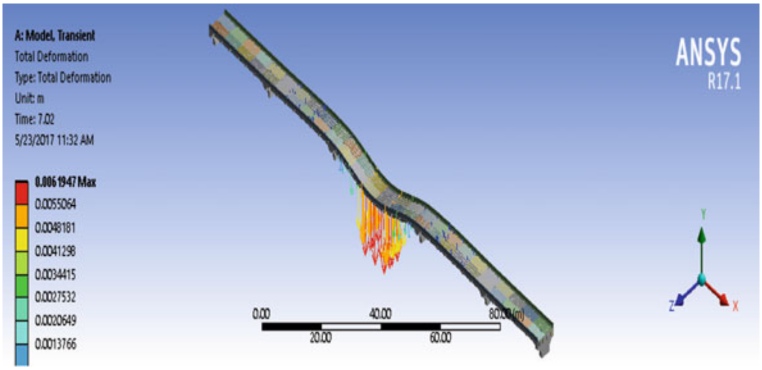
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Fig. 5 Total deformation

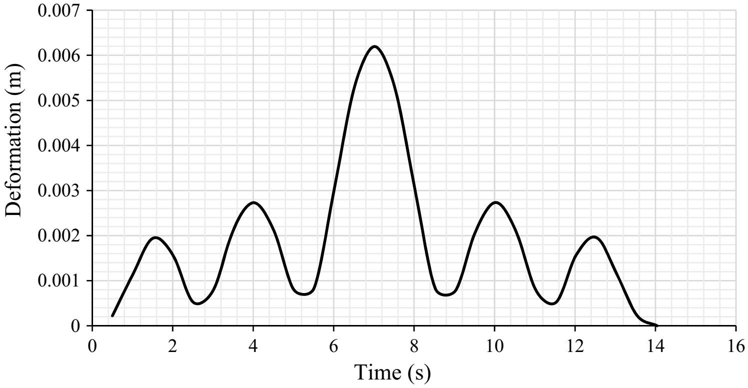

Fig. 6 Deformation occurrence at 156 m bridge

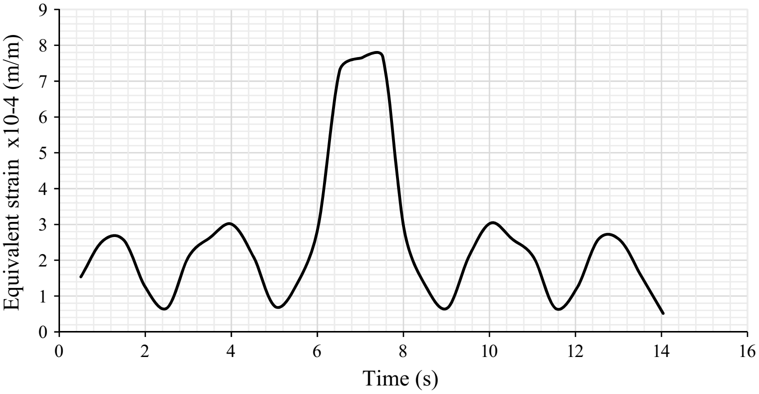

Fig. 7 Equivalent strain variation w.r.t time for 156 m bridge

10 Estimation of Fatigue Life

Total deformation as shown in Fig. 5. The equivalent strain is calculated from Eq. (1)

$$\varepsilon_{eq} = \frac{1}{\sqrt{2}(1+\upsilon)} \times \sqrt{(\varepsilon_{xx}-\varepsilon_{yy})^2 + (\varepsilon_{zz}-\varepsilon_{xx})^2 + (\varepsilon_{xx}-\varepsilon_{zz})^2 + \frac{3}{2}(\gamma_{xy}^2+\gamma_{yz}^2+\gamma_{xz}^2)}, \quad (1)$$

where $\varepsilon_{xx}\varepsilon_{yy}\varepsilon_{zz}\gamma_{xy}\gamma_{yz}$, and γ_{zx} are in their usual form, and these data are extracted from the analysis to calculate equivalent strain amplitude.

The maximum amplitude of strain is found at the long span which is in the middle of the integral bridge. The extracted data is shown in Table 4 is equivalent strain amplitude ε_{eq} and it is used in the following formula developed by Mander et al. [8]:

Table 4 Fatigue life result and validation

Total length of bridge	Maximum span (mid) (m)	Equivalent strain amplitude (m/m) × 10^{-4}	Fatigue life in a number of cycles using $\varepsilon_a = 0.0795(2N_f)^{0.448}$ in $\times 10^6$ cycles	Fatigue life (in years)	Fatigue life from ANSYS 17.1 (in years)
156	40	7.67	15.8	76	79.342
161	45	8.88	11.4	63	63.964
166	50	10.1	8.58	54.6	53.234
171	55	11.3	4.72	43.14	42.234

$$\varepsilon_{eq} = 0.0795(2N_f)^{0.448}, \tag{2}$$

where ε_{eq} is strain amplitude in one cycle of loading, and N_f is the number of cycle to failure.

Mostly, the uniaxial test is used for fatigue modeling. It is unreasonable to conduct a fatigue behavior of the material in a 3D state of stress. Though, a 3D state of stress in a real situation is very common.

Therefore, a concept of equivalent stress and strain developed by Stephens and Fatemi [10] to calculate the fatigue life. From Eq. (1) equivalent strain amplitude is calculated and Fig. 7 was plotted for the equivalent strain. Further, this value is used in Eq. (2) to find the value of the number of cycles N_f.

To calculate the fatigue life in years, it is considered from the report of Economic Survey of Delhi [9] that the heavy motor vehicles passing through city bridge are 225,257 vehicles per year. Further, if single-vehicle completes a single fatigue cycle by dividing these number of the vehicle in one year with the fatigue cycle obtained, fatigue life is calculated and shown in Table 4. From Table 4, it is observed that the calculated life from ANSYS is almost the same as the mathematical model.

11 Conclusions

In this paper, a finite element modeling and analysis has been conducted for estimating the fatigue life for the different integral bridge of 156, 161, 166, and 171 m length. Fatigue life is evaluated form strain life-based approach. The finite element modeling confirms that the fatigue life of the integral bridge will reduce when the total strain amplitude increases due to the increase in the length of the bridge. The fatigue behavior of integral bridge of 156 m that was subjected to transient loading of 70-R as per as IRC:6-2014 is studied. Total four types of variation are considered in length of longer span and model is prepared in ANSYS 17.1 design modeler. The Fatigue life of integral bridge was found from the mathematical model of approximately 76 years for an integral bridge of 156 m long with a maximum span of 40 m, and for the bridge of 186 m length with a span of maximum 70 m, it was found to decrease about 15.24 years. So, it can be concluded that as the length of the span between two piers increases the fatigue life decreases.

References

1. Baptiste KT, Kim WS, Laman JA (2011) Parametric study and length limitations for prestressed concrete girder integral abutment bridges. Struct Eng Int 21(2):151–156
2. Dicleli M, Erhan S (2011) Effect of foundation soil stiffness on the seismic performance of integral abutment bridges. Struct Eng Int 21(2):162–168
3. Drucker DC, Prager W (1952) Soil mechanics and plastic analysis for limit design. Q Appl Math 10(2):157–165
4. Fleck NA, Shin CS, Smith RA (1985) Fatigue crack growth under compressive loading. Eng Fract Mech 21(1):173–185
5. Kalayci E, Civijan SA, Brena SF, Allen CA (2011) Load testing and modeling of two integral abutment bridges in Vermont, US. Struct Eng Int 21(2):181–188
6. Kim WS, Laman JA (2012) Seven-year field monitoring of four integral abutment bridges. J Perform Constr Facilities 26(1):54–64
7. Koh SK, Stephens RI (1991) Mean stress effects on low cycle fatigue for a high strength steel. Fatigue Fract Eng Mater Struct 14(4):413–428
8. Mander JB, Panthaki FD, Kasalanat A (1994) Low-cycle fatigue behavior of reinforcing steel. J Mater Civ Eng 6(4):453–468
9. Planning Department, Government of National Capital Territory of Delhi, pp 130–146. http://delhiplanning.nic.in/Economic%20Survey/ES%202005-06/Chpt/12.pdf. Retrieved 21 Dec 2006
10. Stephens RI, Fatemi RA (2001) Metal fatigue in engineering, 2nd edn. Wiley, New York
11. Wagle G, Watt D (2011) Design of integral bridges on M50, Ireland. Struct Eng Int 21(2):202–205
12. White H (2007) Integral abutment bridges: Comparison of current practice between European countries and the United States of America. Special Report 152, Transportation, Research and Development Bureau, New York State Department of Transportation, Albany, NY
13. Yannotti AP, Alampalli S, White HL (2005) New York State Department of Transportation's experience with integral abutment bridges. In: Proceedings of FHWA conference on integral abutment and joint-less bridges, Federal Highway Administration, Washington, DC, pp 41–49