Reconstruction vs Retrofitting of a Bridge for Sustainability

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Abstract: *Bridges face the risk of being damaged by natural and manmade disasters. Old bridges are more vulnerable in such situations. The common practice is removing these damaged bridges and constructing new ones. However, repairing, retrofitting and reusing damaged bridges could be economical and less time consuming and hence more sustainable than building new bridges. There are various methods to assess the possibility of improving old and / or damaged bridges using modern day techniques. This paper is a case study for using one of such assessment procedures on a damaged railway bridge in Puttalam, Sri Lanka. The bridge concerned is 34m long, single spanned, double lattice girded, wrought iron Railway Bridge, which was built about 40 years ago and damaged and displaced from its abutments by floods. The paper discusses the method used to determine the possibility of reusing the bridge by conducting a series of tests on the temporarily erected bridge and using a finite element model. It also presents results of tests carried out after the bridge was repaired and retrofitted. The results show that retrofitting has made substantial improvements to the bridge.*

Keywords: *truss bridge, condition assessment, finite element model, validation, fatigue life, retrofitting*

1. INTRODUCTION

Bridges constructed over waterways and the sea face the risk of being damaged by floods and water waves. Since flooding has become more severe and common due to climate change etc., the risk of damages to bridges too has increased. Therefore, finding methods to repair and reuse bridges damaged by floods has become imperative.

There are methods to assess the possibility of improving damaged bridges and these methods mainly depend on the future fatigue life of bridge elements. Most widely used code of practice, BS 5400: Part 10: 1980 is one of the sources for the procedure of fatigue life assessment. However, this code has been prepared for the UK and with the use of statistics of roads and railways of the UK. Therefore using such codes without due care and modifications for local conditions may provide misleading results. There are other methods such as the method introduced by *Siriwardane et al* (2009). The principal behind this new method is, predicting past stress histories of critical bridge elements using present day measured strains and applying damage indicator based sequential law to estimate the fatigue life. The fatigue life estimate in this study was done by using a combination of BS 5400: Part 10: 1980 and the new method mentioned above.

This study concerns a 34m long, 5.2m wide, single spanned, double lattice girded, wrought iron railway bridge, located at Puttalam (Bridge No. 02 on the railway track between the Puttalam Cement Factory and Limestone Quarry, used for limestone transport by trains) which was built about 40 years ago and damaged and displaced from its abutments by floods. The bridge was then placed on temporary timber abutments for several years.

With the increase in cement production, the owners of the company wanted to use heavier engines (locomotives) on this railway track with increased number of trips. Therefore, there was a need of an assessment for the bridge in order to determine whether the bridge can be used further or should be demolished and a new bridge built in its place.

In order to do the assessment, a condition survey was carried out and then an analysis was done by modeling the bridge by using SAP 2000 program and validating the model by conducting loading tests on the temporarily erected bridge. Both static and dynamic loading tests were carried out by using an M2 locomotive with 6 numbers of 13.16 ton axles for 5 different loading cases to measure the displacement, strain and acceleration at pre-determined (critical) members of the bridge. Using the validated model, the ability of the bridge for higher loading situations was verified and the future fatigue life of the bridge was found to be 30 years for critical members. Therefore it was decided that rehabilitation of the bridge with necessary retrofitting works will be more sustainable than demolishing it and constructing a new one. The bridge is now in use after being repaired, retrofitted and placed on new abutments.

2. CONDITION SURVEY

During the condition assessment, the bridge and individual elements were measured including the sizes of webs and flanges and their current thicknesses, thicknesses of gusset plates, sizes of rivets and bolts etc., (i.e. main girders of the bridge are of equal span, each 33.65 m end to end, cross girders are placed at the panel points of the main girders and also at the centres of each panel, there are two longitudinal girders connected between cross girders in each panel and there are bracings between main girders, the rail is of gauge 1.75m and etc.).

Several deficiencies were identified during visual inspections such as corroded places in the bridge deck and in load carrying members, missing bracings, missing timber sleepers, improper arrangement of sleepers, improper alignment of the rail track on the bridge deck, increased thicknesses of the members due to oxides, missing rivets, replacements of rivets by nuts and bolts and etc., as shown in figure 1.

Corroded load carrying elements

Defective connections

Missing elements and rivets

Temporary abutment

Figure 1 Defects observed during condition survey

3. ASSESSMENT

3.1. Modelling the bridge using ASP 2000

The bridge was modelled using SAP 2000 as a three dimensional frame element model. Effective measured thicknesses were applied for the members of the model as much as possible. Rivet connections were assumed as fully fixed and rotational stiffness behaviour with a magnitude of 18,200 kNm/rad was assumed at connections of cross girders and bottom chord of main truss girder (Siriwardane et al., 2009). Figure 2 shows the view of the finite element model.

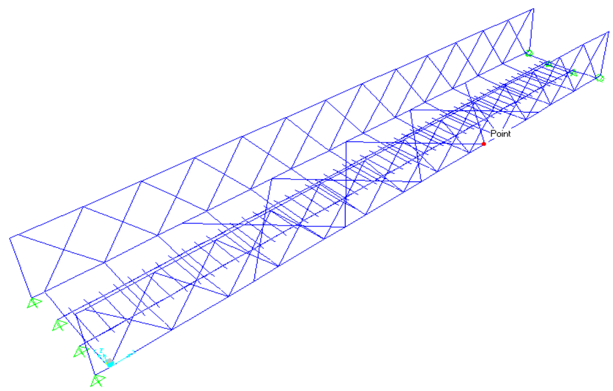

Figure 2 Finite element model of the bridge

3.2. On site loading tests

A series of tests were carried out on site in order to determine the behaviour of the bridge under loading, dynamic factors and for the validation of the finite element model.

An M2 engine (6 Nos., of 13.16 ton axels) was used for loading the bridge at 5 separate loading cases; the center of the engine stopped at 1/4 of the length of the bridge, stopped at mid span of the bridge, stopped at 3/4 of the length of the bridge, the train traveling at a speed of 10 km/hr and the train traveling at a speed of 20 km/hr.

In all the loading cases, displacement measurements (horizontal and vertical) of the mid span of the main girder were measured using 2 displacement gauges, strain measurements at four selected locations were obtained by using strain gauges and acceleration at the mid span using an acceleration gauge.

3.3. Validation of the model

A comparison between the onsite measurements and measurements obtained from the model for similar loading cases are given in table 1. As the readings from onsite displacement and strain gauges and the numerical results obtained from the model are quite close, it was concluded that the model would behave in a similar way to the actual bridge. Therefore the model was used to find numerical results of anticipated loads of the bridge.

Table 1 Comparison of onsite measurements and measurement from the model for the centre of the M6 engine at mid span

Description	Onsite measurement	Measurements obtained from the model
Horizontal displacement	1.46 mm	0.86 mm
Vertical displacement	15.36 mm	12.77 mm
Strain gauge 1 reading	108.05 με	99.56 με
Strain gauge 2 reading	239.50 με	241.94 με
Strain gauge 3 reading	58.07 με	48.62 με
Strain gauge 4 reading	18.56 με	11.53 με

3.4. Checking the bridge for anticipated higher loading

The model was loaded with an engine of weight 100 tons (with 6 axels) which is the anticipated engine which will be used on the bridge in the future. Then the strains, stresses and displacements at critical members (elements) were observed. Figure 3 shows the critical members and table 2 shows the stresses developed in those members against the yield strength and hence the factors of safety of each member.

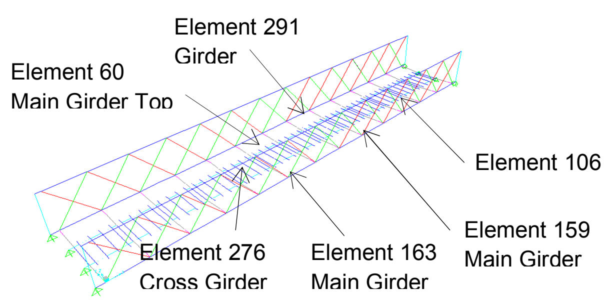

Figure 3 Critical elements of the bridge

As the factors of safety of all the critical members are within reasonable limits, it was decided that the bridge is safe for 100 ton engines subject to further analyses and improvements as mentioned in the next chapters.

Table 2 Factors of safety for critical members

Critical member	Yield stress / MPa	Developed stress/ MPa	Factor of Safety
276	245	97.953	2.501
291	245	96.781	2.531
60	245	68.916	3.555
106	245	60.515	4.049
159	245	96.313	2.544
163	245	64.968	3.771

3.5. Checking the future fatigue life of the bridge

In load carrying structural elements, due to repeated applications of stresses that are not sufficient to cause failures by a single application create cracks which propagate gradually until failure of the element. These failures are called fatigue failures.

Fatigue life estimation was done using the methods given in BS 5400: Part 10: 1988 with required modifications as described by *Siriwardane et al* (2009) such as dynamic factors for different engine types used in Sri Lanka (i.e. 1.30 for diesel engines). The S-N curve for wrought iron was taken from the report "District line fatigue of riveted under bridges, Infrastructures Consultancy Services, London Underground Limited, June 1998". It was assumed that the compressive stresses do not contribute to fatigue damage. The assessment was done only for the 3 most critical members.

Key parameters in fatigue life calculation are, f_{max} which is the maximum stress in a member during a particular stress cycle, f_{min} which is the minimum stress (due to dead load) in the member during the same stress cycle, were determined using the finite element model.

n (n_1, n_2,..) is the number of yearly repetition of stress ranges that the member is subjected to. The value of n during each time period was found using the daily frequency of trains obtained from the authorities (from train timetables).

N (N_1, N_2…) is the allowable number of repetition of stress cycles before failure. Using the f_{max} and f_{min} of a given cycle in a critical member, the value of N was obtained from the S-N curve for wrought iron mentioned before.

In the calculation of cumulative damage, a constant sequence of trains was assumed and the life span of the bridge was divided into 2 periods, from 1970 to 2000 (diesel engines M2, WDM 6 and carriages) and 2000 to 2010 (diesel engine M2 & carriages) depending on the trains that travelled on the bridge.

Miner summation for 2000 to 2010 for fatigue damage (α_1) for a 10 year period was obtained by the equation;

$$\alpha_1 = (\sum n/N) \times 10$$

Miner summation for 1970 to 2000 for fatigue damage (α_2) for a 30 year period was obtained by the equation;

$$\alpha_2 = (\sum n/N) \times 30$$

Then the cumulative fatigue damage for the period of 40 years from 1970 to 2010 (α) was obtained by the summation of α_1 and α_2;

$$\alpha = \alpha_1 + \alpha_2$$

Then the remaining fatigue damage is given by (1-α).

For the calculation of future life from 2010 upwards, an engine weighing 100 tons (16.7 tons/axel, 6 axels), WDM6 engine and carriages were assumed to be traveling per a given train timetable (anticipated train timetable from 2011) and the stresses in the critical elements were obtained from the finite element model. Then the fatigue damage per year (for future years) α_0 was calculated using the equation;

$$\alpha_0 = (\sum n/N)$$

Then the remaining life of each critical member was calculated using the equation;

$$\textit{Remaining fatigue life} = (1-\alpha)/(\alpha_0)$$

The remaining fatigue life thus calculated is subject to any changes of the train time table and engine (loading) weights.

In this assessment, it was found that the most critical member has a future fatigue life of 30 years.

3.6. Improvements

As per the assessment results, it was decided to reuse the bridge with necessary improvements. Accordingly, following improvements were recommended. (a). Placing the bridge on newly built reinforced concrete abutments, (b). Making the railway track straight near the bridge to reduce lateral stresses when the train travels on the existing curved railway track, (c). Cleaning the steel structure completely using sand blasting techniques, identifying the defective elements and replacing them (these improvements increase the fatigue life of these elements as well as the stiffness of the bridge), (d). Applying a corrosive resistant paint, (e). Placing new steel sections for missing elements and bolts for all missing rivets, (f). Aligning the railway track as smooth as possible to reduce vibration, (g). Placing sleepers at regular intervals, (h). Providing a proper river bank protection and (i). Regular maintenance. Figure 4 shows the bridge after improvement works.

Figure 4 Bridge after improvement works

4. VERIFICATION TESTS

Properties of individual elements as well as those of the whole structure may change due to various actions during its rehabilitation (and retrofitting) works. The bridge discussed in this paper was moved from its previous temporary abutment to new abutments without dismantling it. (Note: the bridge is assembled by rivets). In order to determine the status of the bridge after repair, it was decided to conduct non-destructive tests.

4.1. Verification test procedure

A series of loading tests on the bridge was carried out on 31/12/2011 by using an M2 engine (6 numbers of 13.16 ton axles) under different static and dynamic loading conditions as mentioned below. Deflections and strains at critical locations of the bridge were measured.

The loading cases used are; case 1: the center of the engine was stopped at 1/4 of the length of the bridge and measurements were taken, case 2: the center of the engine was stopped at the mid span of the bridge and measurements were taken, case 3: the engine was allowed to travel at a speed of 10 km/hr and measurements were taken and case 4: the train was allowed to travel at a speed of 20 km/hr and measurements were taken.

In order to take measurements, two displacement gauges were fixed at the mid span of a main girder; one below the flange of the main girder, fixed vertically to measure the vertical displacement and the other touching the web of the main girder, fixed horizontally to measure the horizontal displacement. Strain gauges were fixed at three pre-defined locations on critical elements to measure the strains for all four loading cases.

4.2. Analysis of verification test results

Maximum vertical and horizontal displacements of the bridge at static loading were observed as 6.40mm and 0.16mm respectively. Further at dynamic loading, the maximum vertical and horizontal displacements in the recent test were 6.55mm and 0.45mm respectively. Therefore, when comparing these new results with the displacement values obtained before improvement works (table 1), a clear reduction in the displacement measurements could be seen. Due to the retrofitting works (especially due to replacement of weak elements by new elements and by strengthening connections with the use of bolts where they were missing), the stiffness of the structure has improved.

For the 3 elements in which the strains were measured and stresses were calculated, it was found that the maximum stresses happen when the engine moves at 20km/hr (loading case 4). The factors of safety calculated for these 3 members for loading case 4 are 2.40, 2.28 & 18.04 and they are reasonably safe values.

As the verification tests have shown improvements with regard to deflections of the bridge and reasonable factors of safety for the three critical elements with regard to strains and stresses, it was concluded that the improvement works are successful.

5. CONCLUSIONS

Constructing a new bridge usually consumes more time and money than rehabilitating and retrofitting an existing bridge for reuse. There are ways to assess the possibility of reusing old and/or damaged bridges. This paper explains one such assessment method applied to a damaged steel railway bridge using onsite non-destructive tests, finite element models and principals of fatigue life. Further, the bridge so assessed and retrofitted was subjected to verification tests which have proved that the method used is successful.

Most of the old highway steel bridges and railway bridges in Sri Lanka are nearing the end of their design lives. Knowing the future life spans of these bridges is very important because, then the relevant authorities can plan for their rehabilitation or replacement in advance, thereby contributing to sustainable development. The method described in this paper can be applied practically in Sri Lanka to carry out life assessments of steel bridges.

6. ACKNOWLEDGMENTS

The authors acknowledge the collaboration of the team of experts who worked on the investigation of railway bridge No. 2, Puttalam and the kind support given by Holcim Lanka Pvt., Ltd. The authors also convey their gratitude to the National Research Council of Sri Lanka (Grant No. 11-106).

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