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Effect of HS-CFRP Plates on Fatigue Behaviour of Bridges

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Abstract— Fatigue analysis and study is considered as a significant parameter especially in case of structures like bridges. Overloaded trucks are considered as important cause for the fatigue failure of bridges. Main purpose of the study is to find out fatigue safety factor and check this value is greater than 1.5 as per guidelines. In this study a simply supported steel I-girder bridge with IRC loading conditions is modelled and checking its validity analytically through ANSYS. Then fatigue analysis of this bridge is done and checks it is safe under fatigue loading. Fatigue analyses of different span Indian bridges are done to ensure the fatigue safety. A study of HS-CFRP plates, which are wrapped in the bridges to increase the fatigue safety factor value, is carried out for different spans. It is observed that, fatigue effect is significant for longer spans in terms of safety factor. An alternative method is proposed to overcome the fatigue effect without stiffeners are presented.

Index Terms— Fatigue safety factor, HS-CFRP plates, Overloaded truck, Steel I-girder bridge

1 Introduction

Fatigue failures are the common issues in structural engineering. It is the failure of material caused by the repeated application of loads. It is the progressive and localised structural damage that occurs when a material is subjected to cyclic loading. It is a cumulative effect that causes a material to fail after repeatedly applied load, none of which exceeds the ultimate tensile strength. Fatigue loading is the changes observed in a material under the influence of stress generated during cyclic loading. This is generally represented by plotting a stress cycle curve or S-N curve, where S represents stress and N represents the number of cycles to failure. Fatigue failures are commonly seen in bridges, air craft, pavements, pumps, shaft… Fatigue failures in bridges are the common issues. The causes of failure have been divided into seven categories. They are limited knowledge, design errors, human error, natural hazards, accidents, overloading and deterioration. Consequences of failure can often be seen as a good indicator of the importance of a bridge structure, given its form, function and location within a transport network. They can range from casualties and injuries to structural damage, reduction in network functionality and may also extend into environmental and societal impact. Consequences resulting from bridge failures may be divided into four main categories: human, economic, environmental and social. Overloaded trucks, including some extra heavy trucks, often cause serious safety threats on bridges. They are the one of the main reason for fatigue failure. Overloaded trucks are used to convey heavy vehicles, oil tanks, and heavy machines for industrial and military purpose. The presence of overloaded truck traffic can be the evidence of rapid development of an economy. Fatigue is a great trouble to bridge engineers especially with the use of high strength steel and concrete for construction of bridges. Overloaded truck traffic influences the service life of bridge superstructure. Damage typically occurs in the main superstructure elements like bridge deck, girders, diaphragms, joints, bearings. Traffic volume and truck weights have been increasing with our growth and technical development. Bridges are currently subjected to dynamic actions of variable magnitude due to convoy of vehicles crossing on deck pavement. As a result, a series of stress variations or stress cycles are induced in bridge components. This causes nucleation of fractures or even their propagation on bridge deck structure. Thus fatigue failure of bridge occurs due to overloaded truck. Therefore, as with increase in truck loads with our development the damage on highway infrastructure increases.

2 Methodology

From the papers referred, a paper was selected to model a steel I-girder bridge which is designed by AASHTO code. The bridge consists of five identical I-girders, concrete deck and four diaphragms. The bridge has a span length of 16.76 m and roadway width of 9.75 m. The steel girders are spaced 2.13 m apart and the thickness of deck is 0.20m. The cross section of the bridge is shown in Fig.1. The steel I-girders have a height of 1.61 m. The cross section of the bridge is as shown in Fig.2. The finite element software ANSYS 2015 was used to model the structure. A 3D model of the above mentioned bridge was created. The correctness of the model was confirmed by validating the results given in the journal and that evaluated using the software. Another bridge having the same span of the previous one with IRC loading conditions was modeled in ANSYS software. Advanced study was performed to get the value of fatigue safety factor of those bridges. Fatigue analysis was carried out to find the fatigue safety factor. This fatigue safety factor value was checked whether it was greater than 1.5 (as per guidelines), to ensure the fatigue safety of those bridge.

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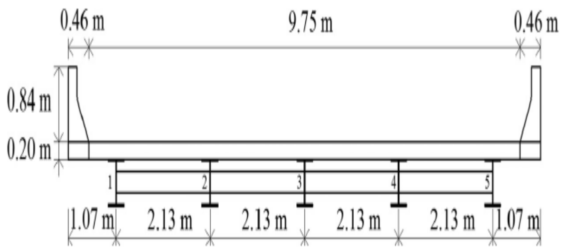

Fig.1 Cross section of the bridge

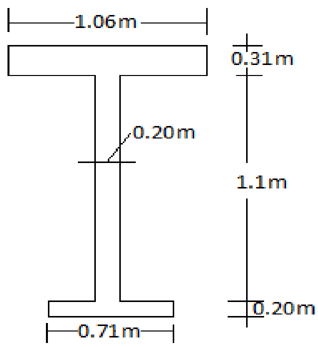

Fig.2 Cross section of the girder

The study is further extended to wrapping the bridges those are not safe under fatigue loading by HS-CFRP plates. The properties of the HS-CFRP plates were verified by validating a steel beam which is wrapped by HS-CFRP plates. The fatigue safety factors of the bridges were increased by increase in the number of layers of HS-CFRP plates. Thus the fatigue analysis was carried out to find the number of layers of HS-CFRP plates required to make the bridges safe under fatigue loading. Thus the fatigue analyses of long span bridges without stiffeners were done and provide an alternative method to overcome the fatigue effect.

3 DESIGN METHODOLOGY OF THE SELECTED BRIDGE

To investigate the fatigue failure of the bridges in India, the fatigue analysis of the bridge is done with IRC (Indian Road Congress) loading conditions. In this project, first a bridge is designed with IRC loading conditions. The span and width of the bridge, cross section of deck and diaphragms are same as that of the bridge which is designed by AASHTO code. To simulate the overweight truck IRC Class - AA tracked vehicle is considered as it gives more severe effects.

Initially self-weight of the concrete part of the bridge deck was calculated. Then the maximum dead load bending moment and maximum shear force were calculated. For calculating the live load B.M. and S.F, IRC- AA tracked vehicle was chosen. And the maximum live load B.M. and S.F. were calculated by placing the wheel at the centre of the beam. Then the dimensions of bridge was calculated.

The economical depth of girder is given by,

$$D = 5\sqrt[3]{M/\sigma bc}$$

Where, M = design bending moment

σ_{bc} = bending compressive stress

From this equation, it was assumed that the depth of web is 1000 mm and the thickness of web is 15 mm.With these dimensions of the web, the shear stress in the web is calculated by using the formula:

Shear stress = design shear force / area of the web

This should be less than average permissible shear stress.

Approximate flange area required is given by,

$$A_f = \frac{M}{\sigma bc * d} - \frac{Aw}{6}$$

Where, Aw = area of the web

Flange width may be taken as L/ 40 to L/ 45 and flange thickness is A_f / flange width.

Thus the flange width was assumed that 450 mm and falnge thickness was taken as 30 mm.

With these dimensions of the flange, bending tensile stress should be less than bending compressive stress

Bending tensile stress is calculated from the formula:

Bending tensile stress = (M*y) / I

Where, y = over all depth of the section / 2

I = moment of inertia of the section about neutral axis

Now the deflection of the whole section should be checked. Initially centroid of the section was calculated using the formula shown below the section was transformed to concrete using modular ratio

$$\bar{Y} = [A_1Y_1 + 5M\,(A_2Y_2+A_3Y_3+A_4Y_4) + 4M\,(A_5Y_5)] / (A_1 + A_2+ A_3+A_4+A_5)$$

A_1 = Area of the concrete deck

A_2 = Area of the bottom flange of steel girders

A_3 = Area of the web of steel girders

A_4 = Area of the top flange of steel girders

A_5 = Area of the steel diaphragms

M = modular ratio

Now with the knowledge of parallel axis theorem moment of inertia of the transformed section was found out

$$I_{xx} = BD^3/12 + (A_1r^2)$$

B = Width of the concrete section

D = Depth of the cross section

Since the bridge is a simple supported one, the deflections corresponding to live load and dead load are found out using the below mentioned formulae. IS800 has been used to obtain the deflection limit.

$$\Delta = (5W_1L^4/384E_c\,I_{xx}) + (W_2L^3/48E_cI_{xx})$$

W_1 = self-weight of the bridge

W_2 = weight of the truck

E = modulus of elasticity

Deflection limit is calculated as a check to ensure the calculated deflection fall within the limit

$$\Delta_{limit} = L/325$$

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Then the span of the bridge is increased by 3m and the corresponding design of bridge is done as same as above. While designing the bridge the width and thickness of the deck slab is kept constant. Only the span of the deck was increased by 3m and the corresponding variations in the dimensions of girder was calculated. The bridge is thus designed for some spans and the dimensions of girder are shown in Table.1.

Table.1 Designed Dimensions Of Girder Under Different Span Of Bridge

Span (m)	Flange Width (mm)	Flange Thick-ness(mm)	Web Thick-ness(mm)	Web Depth (mm)
19.76	475	30	20	1150
22.76	500	30	25	1200
25.76	525	25	30	1250
28.76	550	25	35	1300
31.76	575	25	40	1350
34.76	600	20	45	1400
37.76	625	20	50	1450
40.76	650	20	55	1500
43.76	675	20	60	1550
46.76	700	15	65	1600
49.76	725	15	70	1650
52.76	750	15	75	1700

4 Fatigue Analysis

The majority of structures involve parts subjected to fluctuating or cyclic loads. Such loading induces fluctuating or cyclic stresses which leads to fatigue failure. Therefore, fatigue analysis of the structure is important. Fatigue analysis is done by two methods: stress- life or S-N method and strain- life method or E- N method. The stress- life or S-N analysis estimates the time required to initiate and grow a crack until the component breaks into parts. The strain- life (E-N) analysis estimates the number of cycles required to initiate a crack. We can perform both S-N analysis and E- N analysis in ANSYS workbench. While doing S-N analysis, input the S-N curve of each material in altering stress mean stress. While doing E-N analysis, input the strain life parameters for each material.

Here the fatigue analyses of those bridges are done by stress-life or S-N curve method. The altering stress Vs life cycle graph of steel is already assigned in ANSYS engineering data. The altering stress Vs life cycle graph of concrete is input in the altering stress mean stress details. Fatigue tool inserted in the solution, and the fatigue analysis is done. Here the fatigue analysis is done to obtain the fatigue safety factor which is the important parameter in design.

The value of fatigue safety factor should be greater than 1.5, as per guidelines. This implies failure of the structure occurs after reaching design life. First the fatigue analysis of the bridge which was designed by AASTHO cod is done. The value of safety factor was 3.6177. Since this value was greater than 1.5 failure of the structure occurs after reaching design life. Hence the bridge is safe under fatigue loading. The fatigue analysis of bridges by IRC loading conditions under different span was done and the values of safety factor of those bridges are shown in Table.2.

Table.2 Value of safety factor under different span of bridge

Span (m)	Safety Factor
16.76	3.01
19.76	2.09
22.76	1.7
25.76	1.14
28.76	0.72
31.76	0.57
34.76	0.34
37.76	0.19
40.76	0.086
43.76	0.073
46.76	0.069
49.76	0.055
52.76	0.042

Value of safety factor for first 3 bridges are greater than 1.5. But for other bridges the value of safety factor is less than 1.5. It implies that the bridges with safety factor value less than 1.5, fails before reaching design life. Hence those bridges are not safe under fatigue loading.

5 Fatigue Analysis Of Bridge With HS-CFRP Plates

Since the fatigue effect of the bridges are greatly influenced by wrapping FRP on structures it is decided to wrap FRP on the sides and bottom portion of the girders of the bridges. 4 layers of HS-CFRP plates of 2 mm were taken and its properties were checked by validating a model in ANSYS software. After wrapping FRP on the bridges with safety factor value less than 1.5 the fatigue analysis was carried out. By wrapping 4 layers of HS- CFRP plates almost 40% increase in the safety factor value was occur. But for some bridges the value of safety fac-

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tor was still less than 1.5 after wrapping 4 layers of HS-CFRP plates. So the layers of HS-CFRP plates were increased till the value of safety factor is greater than 1.5. Thus the number of layers of HS-CFRP plates required to make the safety factor value of different bridges greater than 1.5 was find out and shown in Table.3.

Table.3 Value of safety factor with and without HS-CFRP plates and the number of layers of HS-CFRP plates under different spans

Span (m)	Safety Factor without HS-CFRP plates	Number of layers of HS-CFRP plates	Safety Factor with HS-CFRP plates
25.76	1.14	4	1.91
28.76	0.72	5	1.75
31.76	0.57	5	1.63
34.76	0.34	6	1.73
37.76	0.19	6	1.62
40.76	0.086	7	1.68
43.76	0.073	7	1.6
46.76	0.069	8	1.8
49.76	0.055	8	1.76
52.76	0.042	8	1.64

6 Results And Discussions

In this paper the fatigue safety of different bridges was checked by fatigue analysis. First of all, the fatigue safety factor of bridge which is designed by AASHTO CODE with span 16.76 m was calculated. Then the fatigue safety factor of the bridge with same span of the previous one which is subjected to IRC loading conditions was find out. The values of safety factors are 3.617 and 3.01 for the bridge designed by AASHTO code and IRC code respectively. From these values we can understand that the safety factor value for the bridge which is designed by AASHTO code was greater than the other one. But both these bridges are safe under fatigue loading because the values of safety factors are greater than 1.5.

In second case, the fatigue safety of different span bridges which is subjected to IRC loading was find out. Table.2 shows the values of safety factor for different span bridges. From Table.2, it is find out that the value of safety factor decreases with increase in the span of the bridge. For long span bridges the value of safety factor is very small. This implies these bridges fails before reaching design life. Hence those bridges are not safe under fatigue loading.

The fatigue analysis of the bridges which is wrapped by HS-CFRP plates shows that the fatigue safety factor values of those bridges were increased. By wrapping 4 layers of HS-CFRP plates, almost 40% increase in safety factor value was occur. It is also find out that the safety factor value can be increased by increasing the number of layers of HS-CFRP plates. Table.3 shows the change in value of safety factor by increasing the number of layer of HS-CFRP plates. From this it is find out that the layers of HS-CFRP plates are different for different span. The number of layers of HS-CFRP plates should be increased to get the desired safety factor. For long span bridges the number of layers are higher than that of small span bridges. Fig.3 shows the relation between the number of layers of HS-CFRP plates with increase in the span of bridge.

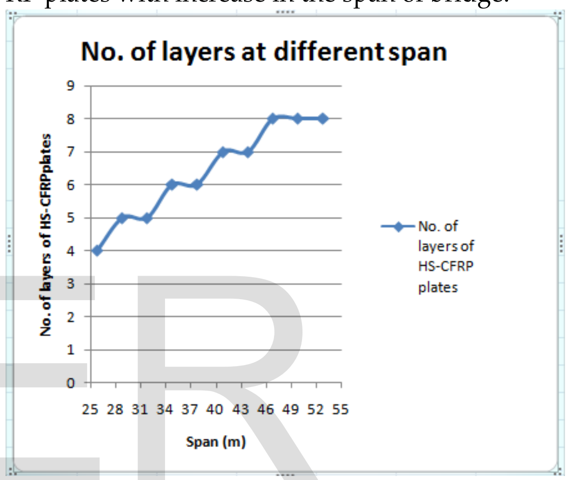

Fig.3 Relation between no. of layers of HS-CFRP plates with increase in the span of bridge

7 Conclusion

The investigations conducted on the fatigue analysis of bridges have made a detailed study on bridge structures from the literature reviews. A 3D finite element model was successfully made for the transient analysis and fatigue analysis.

- The fatigue analysis of the bridges having a span of 16.76 m which is designed by AASHTO code and IRC loading conditions was done to find out fatigue safety factor
    - The values of fatigue safety factor obtained are 3.6177 and 3.01 for AASHTO code and IRC loading conditions respectively.
    - Since those fatigue safety factor value were greater than 1.5, the fatigue failure of the bridge occurs after reaching the design life. Hence it is found that the bridges are safe under fatigue loading.
- The fatigue analysis of bridge which is designed by IRC loading conditions with different span was done,

to know the change in fatigue safety factor with increase in the span of bridges.

- It was found that the value of safety factor was decreases with increase in span.
- For some spans, the fatigue safety factor was less than 1.5, which means the fatigue failure of the bridge occurs before reaching the design life. Hence it is found the bridges are not safe under fatigue loading.
- But these bridges are statically safe and it requires redesigning of the bridge, in order to make it safe under fatigue loading.
- Since the dimensions of girders are comparatively higher due to redesigning, it is not economical to construct such large bridges.
- As an alternative, HS-CFRP plates having 2mm thickness were wrapped on the sides and bottom portion of girders of the bridges and the value of fatigue safety factor was increased

➢ Fatigue analysis of the bridges with different layers of HS-CFRP plates were done

- It was fond that by wrapping 4 layers of HS-CFRP plates, about 40% of safety factor value was increased and by wrapping 5 layers of HS-CFRP plates, about 60% of safety factor value was increased.

➢ The number of layers of HS-CFRP plates for different span of bridges were find out. Hence it is fond that by suitably increase in the number of layers of HS-CFRP plates, the bridges can construct at any span with safe under fatigue loading and economical in construction.

➢ Fatigue effect is significant for longer spans in terms of safety factor. An alternative method is proposed to overcome the fatigue effect without stiffeners.

8 Future Scope

Future scope of the study aims in varying the HS-CFRP plate configuration and plate thickness and check the increase in safety factor value. Future study could also include the effect of different type of FRP plates on fatigue analysis of bridges.

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