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Retrofitting to Alleviate Effects of Corrosion in Cross Girders Under Inner Rail of Curved Railway Bridges

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Abstract: The main railway line which spans from Colombo Fort to Badulla, is one of the nine railway lines of Sri Lanka Railways (SLR). The track alignment of the upcountry section (Rambukkana to Badulla) of the main line was defined about 150 years ago and it has a number of bends with sharp curves. Curved railway bridges are the bridges having railway bends on the bridge to bring gradual change of track direction. When considering with the total number of curved railway bridges, around 75% of curved bridges are located in the upcountry section of the main line. Corrosion of the cross girders beneath the inner rail of a railway bend is the most common problem encountered in curved bridges in the main line. In this study, the reason for corrosion of cross girders of curved railway bridges was investigated through a detailed study of two corroded curved truss bridges in the upcountry section of the main railway line. Current strength of bridge materials and its microstructure were investigated with in-situ hardness measurements and microscopic examination, respectively. Validated numerical models were developed and model results showed that cross girder location beneath the inner rail experienced the highest stresses. These higher stresses are the most logical reasons for corrosion initiation of the cross girders. Further, four repair options were proposed to upgrade these two bridges and their respective numerical models were prepared and analysed. Option 1 is the introduction of the trough section which is the common practice of SLR. Option 2 is the increase of web thickness by welding a steel plate on to the web of the cross girder. Option 3 is the attaching of two steel plates to the top and bottom flanges of cross girders. Option 4 is the combination of Options 2 and 3. Repair Option 1 was not feasible since analysed results showed higher stresses than those of the existing bridges. Options 2, 3 and 4 showed lower stresses than those of existing bridges. Considering the economical and practical aspects of railway operation, it was concluded that Option 2 (increasing web thickness only) is the optimum repair option for the strengthening of corroded curved railway bridges.

Keywords: Cross girder, Curved railway bridge, Numerical modelling, Repair and retrofitting

1. Introduction

The Sri Lankan railway network was implemented by the British Colonial Government in 1864 under the governor, Sir Henry Ward. There are nine lines in Sri Lanka Railway (SLR) network as Main line, Coastal line, Kelani Valley line, Puttalam line, Matale line, Trincomalee line, Batticaloa line, Mannar line and Northern line. These nine lines are based on three operating locations: Colombo (Maradana), Nawalapitiya and Anuradhapura. The total length of these nine networks is 1508 km with 5ft 6 in (1676 mm) broad gauge track [6]. The main line was initially built as a transporting mode of coffee and tea from upcountry to Colombo.

SLR has nearly 1200 railway bridges and culverts and 99% of these structures are made of iron or steel [4]. Some of these bridges were constructed during the British colonial period and over 100 years old. Railway curved bridges are provided in regular bends of the railway to bring a gradual change of direction. This situation occurs where the alignment of a railway track changes its direction because of unavoidable objects (hill or lake or other

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geographical obstacle) or conditions. Therefore, easing of movement of train at this point, a curve railway bridge is provided. Curved bridges are located mainly in the main line, Matale line and KV line as shown in Table 1.

Table 1 - Distribution of curved bridges and culverts in Sri Lanka Railways

Railway line	Total bridges and culverts	Curved bridges and culverts	% of Curved bridges and culverts
Main Line	263	70	27
Matale Line	42	13	31
KV Line	231	10	4

Upcountry (Rambukkana to Badulla) section curved bridges are subjected to locomotives of load classes of S12, M9, M6, M2, M2-C, M5, W3 which are broad gauge locomotives having a maximum axel load of 18.5 tons and having a minimum speed of 32 km/h (20 miles/h) [10]. Axle load is first transferred to two curved rails and then beneath longitudinal timber planks which are supported on cross girders. Timber planks are placed below the rails and fixed to the cross girders through pocket plates. Further, stringers (rail bearers) are not provided in curved bridges. Cross girders are supported on top chords of trusses.

In upcountry curved railway bridges, corrosion of the cross girder section beneath the inner rail has been observed. Such corrosion is critical in some of the upcountry railway bridges. Ignoring such a corrosion issue would aggravate local buckling phenomena of the cross girders violating the safety of bridges. Figure 1 shows two views of corrosion of curved railway bridges.

(a)

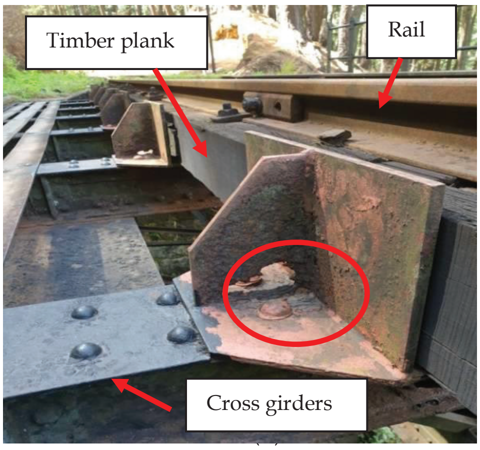


Figure 1 – Two views of corrosion in a curved bridge

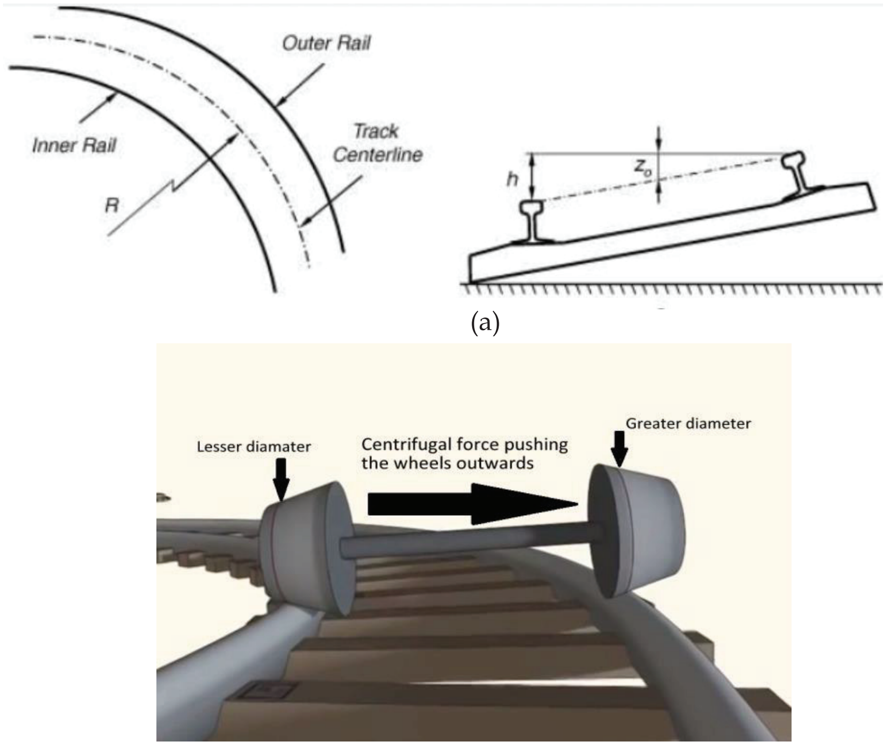
Further, SLR has found difficulties in laying longitudinal timber planks over cross girders to support two rail lines and maintenance cost of curved bridges are therefore higher compared to other types of iron/ steel bridges.

It is essential to identify the causes for corrosion [2 & 3] effect of cross girders and thereby reduce the maintenance cost and increase the durability of the curved bridges. In this aspect, SLR has proposed a solution by laying trough sections between cross girders in the existing curved bridges. Further, it is essential to establish scientific and engineering principles for such repairing option.

The main objectives of the study are identifying the corroded areas in the existing curved bridges, finding possible reasons for such corrosion initiation leading to identifying the feasibility of possible repair options and presenting the optimum repair option among them.

2. Track Geometry

Curved tracks are designed in such a way that the outside rail line is elevated than the inner rail to produce the necessary centripetal force required to keep the train moving in a curved path. The elevation difference between the outer and inner rail at a horizontal curve is defined as the super elevation. Proper super elevation allows a train to safely turn and will make passengers comfortable. Figure 2 shows a typical curved track in a railway line.



(b)

Figure 2 – Track geometry of a curved bridge

Centrifugal force is the outward pull on a train traveling in a horizontal curve. As a train travels in a horizontal curve, centrifugal force is counterbalanced by the train weight component due to railway super elevation and by the side friction between wheels and rail track.

Super elevation and side friction are the two factors that stabilize a turning train. Inadequate super elevation can cause trains to skid as they travel through a curve, resulting in a derailment.

3. Methodology

Out of 70 curved railway bridges in the main line, 35 curved railway bridges are located in the up-county section of the main line. Among these bridges, two bridges spanning 60 ft and 80 ft were selected for the study, as two bridges have shown extensive corrosion in cross girder sections. These two bridges are lattice girder deck spanned bridges having cross girders, main girders and bracings as structural elements. Two bridges have been in operation since 1894.

3.1 Case Study I: Bridge Between Haputhale and Diyathalawa (60 ft Bridge)

The bridge was constructed in 1893 by the then British government and initially built as a transporting mode of coffee and tea from up-country to Colombo. It is located at 159 miles and 23 chains away from Maradana railway station.

The bridge has three lattice trusses with equal distances and a total of seventeen cross girders. Cross girders are supported on the top chords of three lattice trusses. Timber planks have been provided between railway line and cross girders in longitudinal direction to transfer the train loads smoothly to the bridge. Overall length of bridge is 60 ft and the clear span is 20 ft. The bridge is made out of wrought iron and substructure of the bridge consists of two stone masonry abutments, having pinned end support and free end support. Two views of the bridge are shown in Figure 3.

Wet weather condition prevails with an average annual rainfall of 1800 mm in the bridge situated between Haputhale and Diyathalawa. The temperature is normally 23^{o}C and relative humidity is 63%.

Signs of corrosion were found mainly in web sections of the cross girders under the inner rail. Mostly affected cross girders are 5, 6, 9, 13, 14, 15 (from Haputhale to Diyathalawa direction). Also, corrosion appears in pocket plates as shown in Figure 1 (b).

Figure 3 - Two views of the case study bridge I

3.2 Case Study II: Bridge between Diyathalawa and Bandarawela (80 ft bridge)

The bridge located between Diyathalawa and Bandarawela was constructed in 1893 under the British government and it is also a lattice girder deck span bridge. The bridge has an overall length of 80 ft. It comprises three lattice trusses of unequal distances and a total of 21 one cross girders.

Substructure of the bridge consists of two stone masonry abutments and has fix pinned end support and free end support. It was situated at upcountry intermediate zone, having average temperature of 26 ^{0}C, humidity 57% and annual rainfall of 1400 mm.

A significant level of corrosion is present on the web sections of the cross girders under the inner side of rail track. Mostly corroded cross girders are 5, 7, 11, 13, 14, 16, 20, and 21 (from Diyathalawa to Bandarawela direction).

4. Experimental Evaluation of Bridge Materials

Since two bridges were constructed in 1890's, the type of material of the super structures can be considered to be wrought iron material [1]. However, mechanical properties of wrought iron material have physical uncertainty and

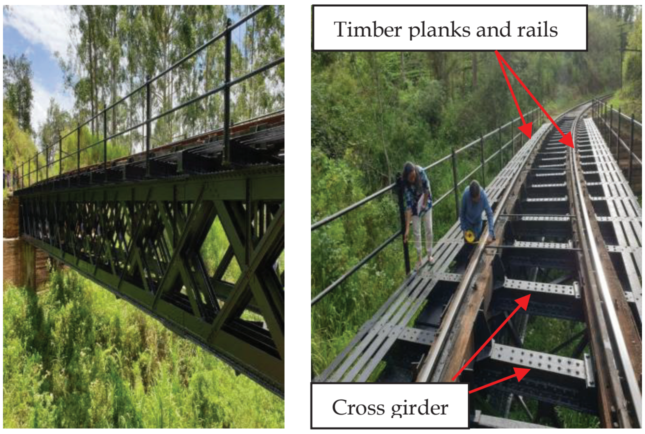


Figure 4 - Two views of the case study bridge II

exact measurement of wrought iron material is important. Three experimental tests were performed to find out material properties. Those tests are hardness test, uniaxial tensile test and microscopic investigation. The first test is an in-situ test and other two are laboratory-based tests.

4.1 Hardness Test

Brinell hardness test was carried out to check the hardness of the material of cross girders and main girders of the bridges. Table 2 shows the obtained Brinell hardness test results.

Table 2 - Brinell hardness test results

Element	Standard Test Bar	Metal	Brinell Hardness Number (BHN)	Ultimate Tensile Strength (MPa)
Cross Girder	2.64	3.69	96	331
	2.48	3.63	97	335
	2.46	3.58	97	335
Main Girder	2.21	2.59	100	345
	2.18	2.46	97	335
Bed Plate	2.35	3.38	103	355
	2.38	3.42	103	355

Using the relationship between Brinell hardness and ultimate tensile strength [7], the latter was determined and given in Table 2. Therefore, the average value of ultimate tensile strength of the material was determined as 342 MPa.
By comparing ultimate tensile strength calculated by Brinell hardness test and that obtained from literature [10], it can be confirmed that these truss structures of bridges were constructed using wrought iron material.

4.2 Uniaxial Tensile Test

Uniaxial tensile test is known as a basic and universal engineering test to achieve material parameters such as ultimate strength, yield strength, % elongation at failure and Young's modulus. These parameters are important for the selection of engineering materials for any application required. Therefore, uniaxial tensile test was carried out in the materials laboratory of the University of Peradeniya on samples collected from Diyathalawa curved bridge (Case study II) during the field visit.

4.2.1 Tensile test results

Ultimate tensile strength (UTS) is the maximum stress that a material can withstand while being stretched or pulled. Table 3 shows the obtained UTS values of bridge material. According to this test, for the analysis, average ultimate tensile strength is considered as 368 N/mm^2.

Table 3 - Ultimate Tensile Strength of the samples of case study II bridge

Sample Description	Diameter (mm)	Length (mm)	Elongation at failure (Eb) %	UTS (MPa)
Sample 01	4.0	21.85	4.74	352
Sample 02	4.0	21.90	13.23	369
Sample 03	3.9	21.80	12.62	382
Average Ultimate Tensile Strength (N/mm^2)				368

4.2.2 Proof stress

Proof stress is the point at which a particular degree of permanent deformation occurs in a test sample. Typically, the stress needed to produce 0.2% of plastic deformation is considered as the proof stress. Since wrought iron material does not show a specific yield strength value, the proof stress is an essential feature in determining the demarcation between elastic and plastic areas. Table 4 shows the proof stress of samples calculated from the graph of tensile test.

Table 4 - Proof stress values of tested specimens

Sample Description	Eb %	0.2% Eb	Proof Stress (N/mm^2)
Sample 01	4.74	0.948	294
Sample 02	13.23	2.646	254
Sample 03	12.62	2.524	276
Average Proof Stress (N/mm^2)			274

According to this test, for the analysis, average proof stress is considered as 274N/mm^2.

4.3 Microscopic Investigation

Microscopic views of fractured specimens were observed through the optical microscope. To carry out the test, specimens were prepared from a sample of wrought iron. Then the specimen was flattened using a flat smooth file and then they were polished by three very fine sand papers.

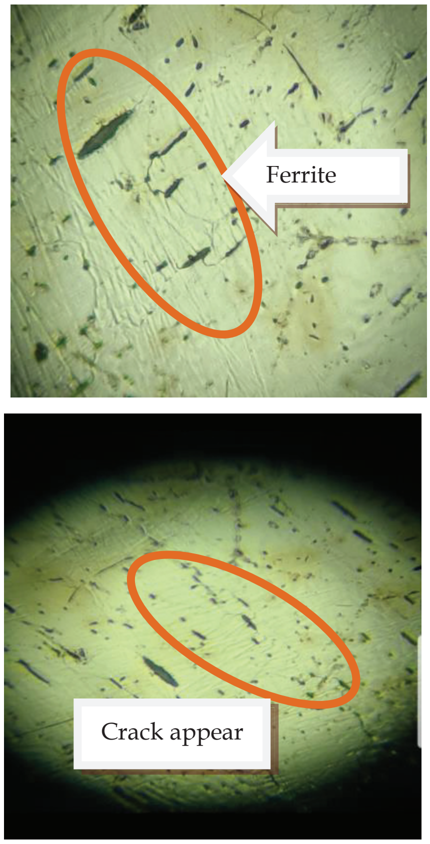


Figure 5 - Microscopic structural view of specimen

Finally the specimen was polished on a polishing machine which contained a velvet cloth on its rotor disc and NH_4Cl /water was added to the sample surface as a smoothing agent. Then the specimen was tested for its micro-structure (magnification of the microscope – x 100).

4.3.1 Test results of microscopic investigation

The microstructure of this material shows higher concentration of dark slag inclusions in ferrite. It is soft, ductile, fibrous variety that is produced from a semi fused mass of relatively pure iron globules partially surrounded by slag as shown in Figure 5.

5. Finite Element Modelling

The internal forces of the selected two curved bridges were determined by using finite element models. For that, general purpose SAP2000 V.20 software package was used [8]. 3D frame elements were used for modelling truss members and boundary conditions were made to pin and free supports at either ends. Wrought iron material properties were used for material parameters. M6 engine weight was used as the imposed load with a dynamic factor of 1.25 to simulate the dynamic impact of the bridge [9]. The analysis included the axle loads by engines and centrifugal forces and self-weights of bridges. Table 5 shows the material properties used in the analysis and Table 6 shows current loading distribution of two bridges. The models were quantitatively validated with support reactions with the weight of the bridges. The weights of bridges are known as these bridges are unit bridges.

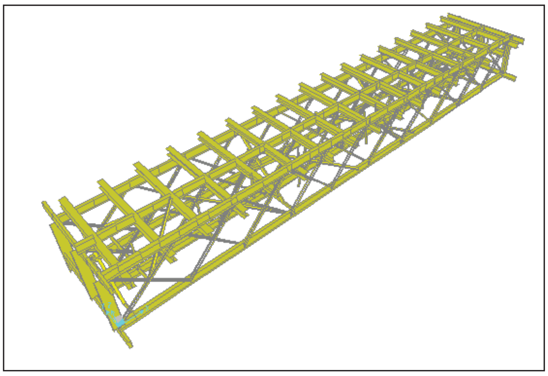
Table 5 - Materials properties of bridge elements

Property	Value (MPa)
Minimum Yield Stress (σ_y)	274
Maximum Tensile Stress (σ_u)	367
Modulus of Elasticity (E)	193,000
Shear Modulus (G)	74230
Poisson's Ratio	0.3
Weight of Unit Volume (ρ)	7.7*10-5

Table 6 - Present schedule of the train crossing the upcountry bridges

Engine types	Engine weight (tons)	Number of Trains in one direction per day
M2	84	2
M5	67	1
M6	84	2
S12	67	4

Figures 6 and 7 show the elevation and plan views of the bridges belonging to the two cases.



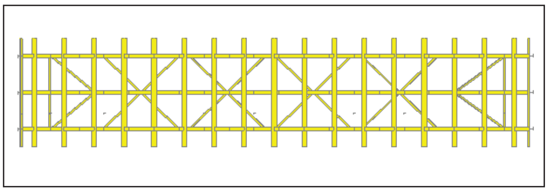
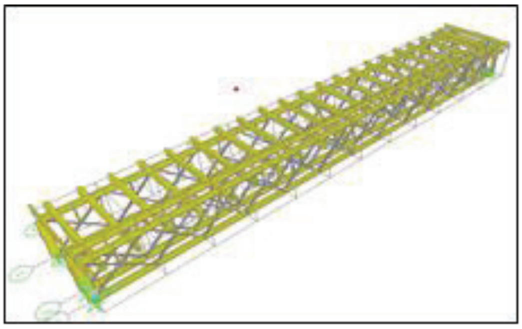


Figure 6 - Case study I FE model (17 cross girders)



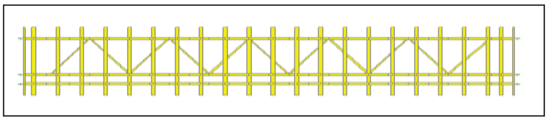


Figure 7 - Case study II FE model (21 cross girders)

5.1. Repair Options of Bridges

Assessment mainly included from two existing models and eight repair models.

- Existing bridge models
  Case Study I - 60ft span bridge
  Case Study II - 80ft span bridge

Bridges with repairing options – (Two case studies)

- ➢ Option 1 – Bridge upgrade by using longitudinal trough spans
- ➢ Option 2 – Increasing the web thickness of cross girders
- ➢ Option 3 – Increasing the flange thickness of cross girders
- ➢ Option 4 – Increasing both web & flange thickness of cross girders

Further, centrifugal force was also used in the analysis. Load combination: Dead load x 1 + imposed load x 1.25 + Centrifugal force, was used in the analysis to represent the serviceability condition of the bridges.

6. Results and Interpretation

Using the validated numerical models, the stress distributions of cross girders of two case study bridges were obtained and results are given in Tables 7 and 8.

Table 7 - Stress distribution of cross girders of case study I

Cross girder	Stress under outer rail (N/mm²)	Stress under inner rail (N/mm²)	Stress at middle of cross girder (N/mm²)
1	100.3	146.7	13.3
2	102.9	208.6	59.7
3	141.9	221.2	46.1
4	187.3	232.8	40.7
5	179.6	252.2	38.1
6	175.8	206.5	33.5
7	158.8	177.2	35.1
8	159.7	183.2	37.3
9	182.9	209.2	42.8
10	152.5	176.3	36.3
11	159.1	188.9	36.7
12	160.1	181.6	31.8
13	175.4	211.1	33.6
14	152.0	187.3	34.5
15	187.0	216.6	58.8
16	145.2	182.7	40.6
17	65.7	125.5	58.0

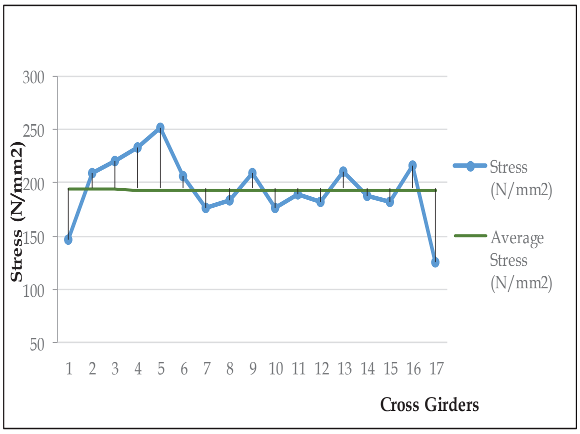


Figure 8 - Graph of maximum stresses on cross girders under inner rail in Case study I

Figures 8 and 9 show the maximum stresses over the cross girders and deviation from the average stress.

Table 8 - Stress distribution of cross girders of case study II

Cross girder	Stress under outer rail (N/mm²)	Stress under inner of cross girder (N/mm²)	Stress at middle of cross girder (N/mm²)
1	307.1	326.4	144.9
2	263.6	305.2	97.3
3	209.0	285.6	70.2
4	167.5	272..0	33.5
5	142.8	276.2	27.4
6	166.8	261.7	22.7
7	169.9	336.7	15.2
8	175.4	337.9	12.5
9	182.6	335.9	9.8
10	185.5	352.3	10.1
11	190.4	358.4	50.1
12	183.0	340.1	6.7
13	185.5	338.2	9.7
14	178.1	334.9	11.7
15	174.1	347.2	15.9
16	168.5	306.3	21.8
17	154.6	223.7	24.6
18	163.7	273.0	32.4
19	208.8	288.4	69.7
20	276.8	288.4	103.2
21	307.1	326.5	149.9

Stress reduction of the cross girders at the inner rail line for the four repair options were determined and the obtained results are shown in Tables 9 and 10.

Figure 9 - Graph of maximum stresses on cross girders under inner rail in Case study II

Table 9 - Percentage stress reduction of options 1, 2, 3 & 4 to stress of case study I

Cross Girder	Percentage stress reduction of options1,2,3 and 4 to stress of existing bridge			
	Option 1 (Introducing trough sections)	Option 2 (Increasing Web Thickness)	Option 3 (Increasing flange thickness)	Option 4 (Increasing both web and flange thicknesses)
1	-35.4	40.1	24.4	61.6
2	-14.3	45.8	45.8	64.4
3	-24.2	46.5	40.9	63.4
4	-24.3	37.7	30.4	56.0
5	-25.3	29.5	22.2	49.0
6	-53.8	25.9	10.1	45.7
7	-75.7	21.3	2.3	40.7
8	-76.1	21.4	2.2	41.2
9	-57.1	16.1	1.6	37.0
10	-76.0	23.3	2.7	42.1
11	-70.8	18.3	1.9	38.9
12	-53.3	26.4	5.7	45.6
13	-40.5	32.9	20.2	52.0
14	-55.6	48.4	33.1	64.4
15	-33.7	57.8	45.1	71.2
16	-2.5	50.8	50.0	67.8
17	-6.4	71.9	69.0	79.2

The stress reduction is defined as absolute ratio of stress reduced of the selected option from the existing model to that of the existing model. According to Tables 9 and 10, Option 1 shows the lowest stress reduction. Option 4 (Increased the web & flange) shows the highest stress difference with existing bridge conditions.

Increasing the top flange thickness is practically difficult due to the presence of rail lines. Therefore, comparing those four options, with the economical and practical considerations in operation, it was concluded that the repair Option 2 (Increased the web thickness) is the optimum solution for the damaged curved bridges.

7. Conclusion and Recommendations

According to FEM analysis, stresses in cross girders under the inner rail are higher than those of outer side. At present, corrosion has mainly occurred in cross girders under the inner side rail. Therefore, the high stress values have triggered the corrosion of cross girder under inner rail.

Four repair options were proposed and their applicability was checked. FEM results show the bridges with trough sections have higher stresses on cross girders than existing bridges (without trough sections). Out of other three options, Option 2 (increasing the web thickness) is seemed to be optimum repair for the bridges.

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Table 10 - Percentage stress reduction of options 1, 2, 3 & 4 to stress of case study II

Cross Girder	Percentage stress reduction of options1,2,3 and 4 to stress of existing bridge			
	Option 1 (Introducing trough sections)	Option 2 (Increasing Web Thickness)	Option 3 (Increasing flange thickness)	Option 4 (Increasing both web and flange thicknesses)
1	-18.8	39.1	23.4	48.3
2	-39.3	35.5	21.1	35.5
3	-41.4	46.7	20.1	57.3
4	-59.1	48.4	10.4	55.9
5	-53.6	51.5	6.7	55.9
6	-59.9	56.0	3.8	57.4
7	-32.6	54.4	0.1	54.1
8	-32.5	53.3	1.0	53.9
9	-32.9	52.8	1.8	54.0
10	-30.0	50.1	3.2	52.9
11	-28.4	49.5	4.1	53.0
12	-34.1	52.0	2.5	53.9
13	-34.7	52.5	1.9	53.9
14	-33.9	53.8	0.9	54.3
15	-34.0	52.8	0.8	53.4
16	-57.8	56.0	3.5	57.3
17	-57.1	53.7	6.8	57.5
18	-56.0	48.3	10.1	55.5
19	-48.6	42.6	13.9	54.9
20	-30.0	60.7	17.5	63.0
21	-52.2	56.1	6.5	56.5

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