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STATIC ANALYSIS OF A REINFORCED SUSPENSION BRIDGE

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ABSTRACT
This paper is based on diseases of an anchor rope bridge and the reinforced cables are putting forward. It changed the original single cable bearing system into a suspension - cable collaboration system. Through the finite element analysis of the bridge after reinforce. The internal force, stress and stiffness index are compared before and after the reinforcement of the structure. The result shows that the scheme makes the stay-cables, main cable and suspenders work together to bear the force. It reduced the burden of main cable and the boom and solved the problem that the original bridge vertical displacement is too large. At the same time also reduce the dead load and internal force under the action of automobile loading structure and improved the carrying capacity of the structure. The reinforcing scheme has certain feasibility. For the reinforcement method is used for reference in the application of the same type bridge reinforcement.

INTRODUCTION

Primary situation of structure
A bridge[Error! Reference source not found.] in Guizhou is the reinforced steel truss suspension bridge by anchor. The length of the bridge is 477.23m and the span arrangement is 18.5+24.1+3×20.5+240+4×20.5. The width of the bridge is 12.6m. The approach span is unboned pre-stressed concrete hollow slab and the main tower is concrete frame structure of door type. The main cable has 19 groups parallel high-strength galvanized steel wire bundle and each has 91Φ5mm group parallel high-strength galvanized steel wire bundle. The suspender adopts 61Φ7mm high strength steel wire rope. The pitch of wore cord in beam is 6m. The general arrangement of structure is in the Fig.1.

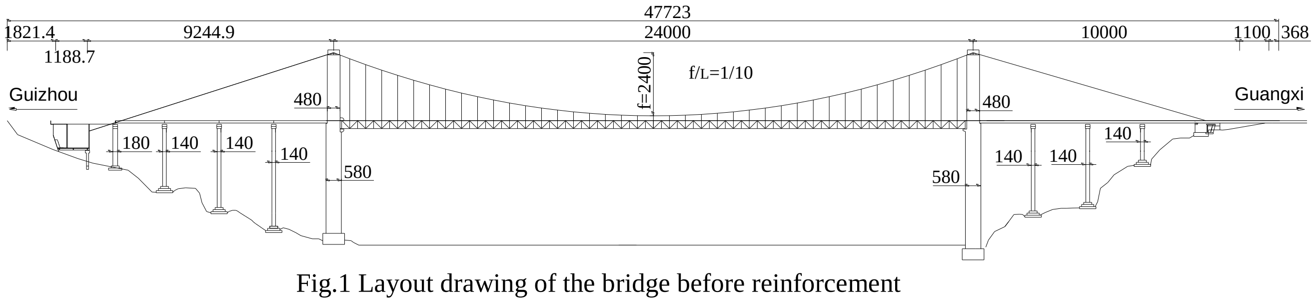

Fig.1 Layout drawing of the bridge before reinforcement

Designing load: two-lane; pedestrian load: 5kN/m; the layout about road crossing: 12.6m.
The cross-section is shown in Fig.2 and the real bridge picture in Fig.3.
The original bridge has been used for many years and it has many problems as follows:

a. The stiffening girder is becoming the S-shape and the constant load tensile is not symmetry. It shakes obviously under the vehicle load.
b. The main cable is still well but the nuts in the anchorage zone are not very well. Some suspenders rust are lost. Stationary steel boilers rust and some set bolt lost.

c. The connecting nuts of steel truss plate are lost. Most beam has vertical lean and thus the steel plate in the middle of the beam comes to nothing in some extent. The welds in the middle of the beam rust badly and some even fracture.
d. The two sides of the main tower have obvious chicken-wire cracking.

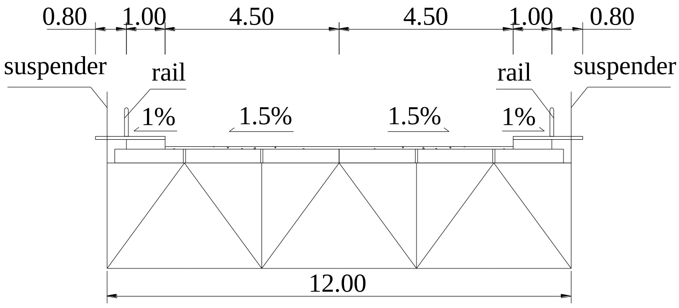

Fig.2 Layout drawing of cross-section

Fig.3 The real bridge picture

e. The concrete of the bridge floor badly damaged and almost all the junctures about the bridge deck slab crushed and exposed reinforcing bar and some badly damaged. The bridge has seepage badly and it causes the erosion. The vibration impact intensified in the traffic. The pavement layer of the suspender has serious breakage, pit slot, exposure, and cracks.

Because of the above problems, the bridge has many significant hazards during the normal use. It is the high time to reinforce the bridge.

Reinforcement scheme

The bridge is using the cable reinforcement[Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.]. It converts the single suspension cable bearing system into haul system. The stay cable, main cable and Suspender are bearing the force together. There are 4 groups steel wire rope and each group has 61Φ7mm parallel Wire cables. They are in the two sides of the owner cable anchor chamber[Error! Reference source not found.Error! Reference source not found.]. There are 2 groups of parallel wire cable in the mid-span and each group has 37Φ7mm parallel wire cable. They are on the top chord. The pitch of wore cord is 12m. The bottom chord of the main joist steel truss has 2 groups low relaxation unbonded steel strand and each group has 12×7Φ5mm low relaxation unbonded steel strand and they adopt the external pre-stressing concrete beam reinforcement. The design load after reinforcement: Highway-I class, two-lane. Cross section arrangement is 9+2×1.0+2×0.5=12.6m. The arrangement plan of reinforcement is shown in Fig.4.

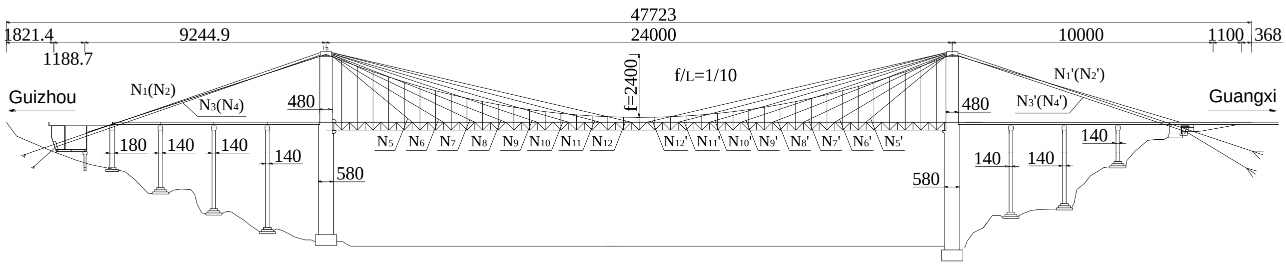

Fig.4 The arrangement plan of the bridge after reinforcement

NUMERICAL MODELLING

Finite element calculation model before reinforcement

The boundary condition in the model about the bottom of the main cable and the bottom of the tower is concretion. The boundary condition between cable in the top tower and the tower is rigid coupling. The stiffening girder has no longitudinal and corner constraint and there is horizontal constraint. There are 1703 space beam elements, 162 cable elements. The beam elements are used to simulate the main girder and cable tower. The cable elements are used to simulate sling and main cable. Calculation model is shown in Fig.5.

Fig.5 The calculation model before reinforcement

The stiffening girder is 16Mn steel, the main cable is Φ5 high tensile steel wire, suspender is the Φ7 high tensile steel wire. The tower is C40 concrete.

The following loading combination are used to check the safety of the structural carrying capacity.
Loading combination: dead load + motor vehicle loading
Allowable stress: $\sigma \le [\sigma_w] = 210MPa$

Finite element calculation model after reinforcement

The model has 1807 space beam elements, 162 cable elements and 48 truss elements. The beam elements are used to simulate the main girder and cable tower. The cable element is used to simulate the sling and main cable and externally pre-stressed steel strand. However, more attention should be paied to the N12 stay cable, it is 120m long, but its tensioning force is 149kN. It can’t be tensiled during the actual construction. Thus the sag has a deep influence on the cable force. The boundary condition in the model about the main cable ends and bottom of the tower is concretion. The boundary condition between cable in the top tower and the tower is rigid coupling. The boundary condition about the cable and tower is rigid coupling. The boundary condition about the stay cable and truss is rigid coupling. Calculation model is shown in Fig.6.

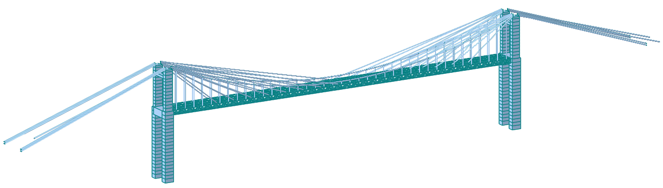

Fig.6 The calculation model after reinforcement

The material of the external pre-stressing are 7Φ5mm low relaxation unbonded steel strand. The material of across the cable are 37Φ7mm parallel wires of high tensile steel. The material of Side span cable are 61Φ7mm parallel wires of high tensile steel. Performance of materials is list in Tab.1 and force of stayed cable shows in Tab.2.

Table.1 Performance of main materials

Material	Steel strand	High strength galvanized steel wire bundle
Elasticity modulus (MPa)	1.95E+05	1.95E+05
Poisson ratio	0.3	0.3
Coefficient of linear expansion	1.20E-05	1.20E-05
Standard strength (MPa)	1860	1670

The self-weight of the structure is 78.5kN/m^3. According to the design, design load road-I and two-lane are adopted.

The crowd loading is 2.5×2×1=5kN/m. The following loading combination can be adopted to check the carrying capacity safety of the structure.

Table 2. Force Tab of stayed cable (kN)

Position	Stayed cable No.		Initial tension
Side span	N1	N1’	421
	N2	N2’	581
	N3	N3’	770
	N4	N4’	655
Main span	N5	N5’	448
	N6	N6’	463
	N7	N7’	449
	N8	N8’	407
	N9	N9’	353
	N10	N10’	285
	N11	N11’	215
	N12	N12’	149

Combination 1: 1.0dead loading+1.0 motor vehicle loading+1.0 crowd loading；
Combination 2: 1.0dead loading+1.0 motor vehicle loading+1.0 crowd loading+1.0temperature effect;
Permissible stress,

Combination 1: $\sigma \le [\sigma_w] = 210MPa$;

Combination 2: $\sigma \le k[\sigma_w] = 262.5MPa$

Allowable stress about the stability problems of columns in combination 1: $\sigma \le [\sigma] = 200MPa$

Allowable stress about the stability problems of columns in combination 2: $\sigma \le k[\sigma] = 250MPa$

STATIC ANALYSIS AFTER AND BEFORE REINFORCEMENT

Calculation of suspender stress

The force of the suspender under various loading combination is shown in the Tab.3.
Before reinforcement:

Dead load + maximum vehicle load: maximum of the suspender is $\sigma = 234.2MPa$; safety factor is $K = \frac{1670}{234.2} = 7.13 > 2$.

After reinforcement:

In the loading combination 2, maximum of the suspender is 534.13kN; stress is $\sigma = 227.5MPa$; safety factor is $K = \frac{1670}{227.5} = 7.34 > 2$.

The safety factor is larger than 2.0 and it is in a safe state.

Main cable stress calculation

The internal force of the main cable under various loading combination is shown in the Tab.4.

Tab.3 Suspender force under various load combination

Suspender No.	Before reinforcement		After reinforcement		
	Dead load	Dead load +Max vehicle load	Dead load	Dead load +Max vehicle load	Max load combination 2
No.1	340.36	451.81	348.57	401.46	448.20
No.2	390.80	467.59	393.06	454.30	471.17
No.3	400.53	511.31	394.44	470.59	484.06
No.4	401.88	523.31	391.84	470.18	483.13
No.5	402.08	527.17	383.82	458.74	471.47
No.6	401.98	527.60	366.52	432.19	444.51
No.7	402.15	529.55	375.19	446.87	459.31
No.8	402.23	530.50	365.27	433.64	445.90
No.9	402.38	530.44	379.27	455.18	467.66
No.10	402.15	530.22	373.17	448.04	460.40
No.11	402.52	530.93	389.38	471.51	484.05
No.12	402.26	530.39	385.62	467.34	479.68
No.13	402.26	530.21	400.81	488.51	500.97
No.14	402.29	530.22	398.36	485.60	497.81
No.15	402.32	530.09	411.47	503.13	515.40
No.16	402.39	530.00	409.48	500.18	512.08
No.17	402.12	529.55	418.98	512.67	524.57
No.18	402.22	529.68	416.75	508.99	520.42
No.19	393.73	519.21	414.03	507.07	518.24
No.20	419.11	549.85	434.68	528.88	540.27

* The Suspender number is changing from 1 to 20 from the direction about Guizhou to mid-span.

Tab.4 The maximum stress and stability calculation of the main truss before reinforcement

Main cable element No.	Before reinforcement		After reinforcement		
	Dead load	Dead load+ Max vehicle load	Dead load	Dead load+ Max vehicle load	Max load combination 2
1946	22379.56	25610.67	23031.59	25650.88	26492.69
1947	22561.51	27314.48	22276.25	25192.08	25939.89
1948	22434.00	27190.38	22146.48	25058.92	25792.78
1949	22295.14	27023.11	22007.74	24902.73	25630.95

1950	22160.17	26857.47	21876.19	24752.68	25476.64
1951	22032.16	26701.21	21752.86	24612.00	25332.12
1952	21911.57	26549.45	21639.19	24482.62	25199.24
1953	21798.61	26407.99	21537.23	24367.03	25080.50
1954	21693.28	26278.08	21439.90	24256.28	24966.77
1955	21595.7	26157.85	21351.80	24156.10	24863.89
1956	21505.93	26042.7	21267.54	24059.60	24764.87
1957	21424.14	25936.66	21191.62	23972.43	24675.43
1958	21350.27	25843.58	21119.95	23889.32	24590.21
1959	21284.5	25759.65	21056.40	23815.20	24514.26
1960	21227.27	25673.49	20998.30	23746.49	24443.88
1961	21178.26	25615.66	20948.48	23686.94	24382.94
1962	21137.48	25549.68	20905.37	23634.43	24329.21
1963	21104.95	25518.16	20870.87	23591.66	24285.49
1964	21080.66	25482.96	20844.31	23557.86	24250.95
1965	21064.2	25455.65	20826.34	23534.52	24227.13
1966	21056.12	25443.22	20817.40	23522.52	24214.89
1967	21056.29	25443.38	20817.57	23522.69	24215.06
1968	21064.67	25456.13	20826.84	23535.01	24227.63
1969	21081.45	25483.75	20845.14	23558.68	24251.78
1970	21106.06	25519.27	20872.02	23592.80	24286.64
1971	21138.91	25551.1	20906.83	23635.87	24330.66
1972	21180	25617.4	20950.26	23688.70	24384.71
1973	21229.33	25675.55	21000.39	23748.56	24445.96
1974	21286.88	25762.03	21058.81	23817.58	24516.65
1975	21352.96	25846.28	21122.66	23892.00	24592.91
1976	21427.15	25939.68	21194.65	23975.42	24678.43
1977	21509.26	26046.03	21270.87	24062.88	24768.17
1978	21599.35	26161.5	21355.42	24159.67	24867.49
1979	21697.25	26282.05	21443.82	24260.15	24970.67
1980	21802.9	26412.28	21541.45	24371.20	25084.69
1981	21916.18	26554.06	21643.71	24487.08	25203.72
1982	22037.08	26706.14	21757.67	24616.76	25336.91
1983	22165.42	26862.72	21881.36	24757.78	25481.77
1984	22300.7	27028.68	22013.19	24908.11	25636.35
1985	22439.87	27196.26	22152.25	25064.62	25798.51
1986	22567.66	27320.64	22282.31	25198.07	25945.91
1987	22299.81	25530.92	22852.64	25386.70	26251.70

* Element 1946 is main cable of side span at Guizhou side, and element 1987 is main cable of side span at Guangxi side

Before reinforcement: From the above Tab we can see that the maximum axial force of the main cable in the combination dead load+ vehicle maximum load is 27320.64kN, $\sigma = 803.5MPa$; safety factor is $K = \frac{1670}{803.5} = 2.08 < 2.5$.

After reinforcement: safety factor in the loading combination 1 is $K = \frac{1670}{754.2} = 2.21 < 2.5$.

Safety factor in the loading combination 2 is $K = \frac{1670}{779} = 2.14 < 2.5$.

Stress calculation of stayed cable

The stayed cable forces under various load combination is in the Tab.5.

Table.5 Force of stayed cable after reinforcement

Stayed cable No.	Maximum cable force (kN)	Maximum stress (MPa)	Allowable stress (MPa)	Safety factor
N1	793	337.9	1670	4.9
N2	975	415.1		4.0
N3	1163	495.4		3.4
N4	1047	445.7		3.7
N5	1455	1021.6		1.6
N6	1264	887.6		1.9
N7	1116	783.6		2.1
N8	983	690.4		2.4
N9	873	613.2		2.7
N10	760	533.6		3.1
N11	649	456.1		3.7
N12	460	322.9		5.2

From the results of the internal force of main cable, we could found: the safety factor of the stay cable about the N5, N6 is a little flat and it can't be satisfied the code requirement. The force about the main cable and suspender has a little reduction. The tensioning force about the stay cable is largely unreasonable and the bearing capacity about some cables have not attended the code requirement.

The main truss chord stress calculation

The maximum stress of main truss is shown in Tab.6 and Tab.7, stability calculation of main truss in Tab.8, and Tab.9 shows the members stress ratio of the external pre-stressed anchor points after reinforcement. In Tab.6 to Tab.9 negative value is compressive stress, and positive value is tensile stress.

Table.6 The maximum stress and stability calculation of the main truss before reinforcement

Component	Top chord	Lower chord	Vertical web member	Diagonal web member
$\sigma_{t,\max}$	126.3	161.5	67.6	95
$\sigma_{c,\max}$	-185.6	-103.2	-48	-76.5
N/A	-158.9	-80.8	-58.7	-62.1
M/W	-26.7	-22.6	10.7	-14.4
Stability coefficient	0.858	0.858	0.329	0.329
Reduced stress	211.89	116.8	167.7	192.8

Table.7 Maximum stress of main truss after reinforcement

Component	Combination 1		Combination 2	
	$\sigma_{t,\max}$	$\sigma_{c,\max}$	$\sigma_{t,\max}$	$\sigma_{c,\max}$
Top chord 1	412.5	-455.4	443.1	-497.4
Top chord 2	211	-354.9	213.2	-366.9
Lower chord	284.7	-198	306.4	-200.8
Inclined and vertical web member	210.1	-180.4	216.1	-183.5

Table.8 Stability calculation of main truss after reinforcement

Component	Top chord 2	Lower chord	Inclined and vertical web member
$\sigma_{c,\max}$	-366.9	-200.8	-183.5
σ_N	-158.3	-153.2	-46.9
σ_M	-208.6	-47.6	-136.6
Stability coefficient	0.858	0.858	0.329
Reduced stress	393.1	226.2	279.2

Table.9 Maximum stress and stability calculation of the main truss before reinforcement

Element No.		81	2061
Combination 1	$\sigma_{t,\max}$	516.8	-238.5
	$\sigma_{c,\max}$	442	-305.1
Combination 2	$\sigma_{t,\max}$	524.9	-236.5
	$\sigma_{c,\max}$	-442.7	-306.9

* In Table.6 to Table.9, top chord 1 is in anchor point of stayed-cable, lower chord is in other point without stayed-cable. Top chord 2 is the anchorage cable in upper chord. The lower chord does not consider externally prestressed anchorage location chord. The stress is tensile stress. $\sigma_{t,\max}$: The maximum tensile stress, $\sigma_{c,\max}$: The maximum compressive stress.

From the above Tab we can see that the main truss chord stress can meet the code requirement. Bar stability can meet the code requirement. Because of the limit about the space in this paper, the stress and stability calculation of the main girder beams is not mentioned in this paper. The results show that the stress of main truss meets specification requirements. But some individual bar's stability don't meet the requirements of specification. The applied of nodal force will cause large damage to the local bars. Bar's stress don't meet the requirements of specification. Bar's stability don't meet the requirements of specification.

Stress calculation of cross beam

Tab.10 to Tab.12 show the result of maximum stress and stability of cross beam that before and after reinforcement. In Tab.10 to Tab.12 negative value is compressive stress, and positive value is tensile stress.

Table.10 Maximum stress and stability calculation of cross beam before reinforcement

Component	$\sigma_{t,\max}$	$\sigma_{c,\max}$	Stress caused by axial force	Stress caused by bending moment	Stability coefficient	Reduced stress
Top chord	81.5	-184.4	-83.6	-100.8	0.671	225.4
Lower chord	201.6	-123.9	1	-124.8	0.633	123.2
Tilted belly poles outside	-0.08	-103.5	-88.1	-15.4	0.329	283.2
Tilted belly poles inside	88.7	-85.6	-35.7	-49.9	0.393	140.7

Vertical web member	20.2	-58.4	-34.2	-24.2	0.329	128.2

Table.11 Maximum stress of cross beam after reinforcement

Component	Combination 1		Combination 2	
	$\sigma_{t,\max}$	$\sigma_{c,\max}$	$\sigma_{t,\max}$	$\sigma_{c,\max}$
Top chord	81.3	-242.5	84.1	-244
Lower chord	196	-55	196.5	-56
Tilted belly poles outside	-61.3	-149	-61.6	-149.7
Tilted belly poles inside	114.8	-79.7	115.6	-79.9
Vertical web member	34.4	-85.8	34.6	-85.9

Table.12 Stability calculation of cross beam after reinforcement

Component	$\sigma_{c,\max}$	Axial force caused by stress	Bending moment caused by stress	Stability coefficient	Reduced stress
Top chord	-244	-115.8	-128.2	0.671	300.8
Lower chord	-56	0	-56	0.633	56.0
Tilted belly poles outside	-149.7	-128.3	-21.4	0.393	347.9
Tilted belly poles inside	-79.9	-49.4	-30.5	0.329	180.7
Vertical web member	-85.9	-55.2	-30.7	0.329	198.5

Rigidity computation

For the flexible suspension bridge, the vertical dis-placement under the vehicle action and the dead load are the leading indicator in measuring the stiff-ness of the structure. The following Fig.7 to

Fig.10 give the main truss vertical displacement un-der the action of dead load and vehicle before and after reinforcement.

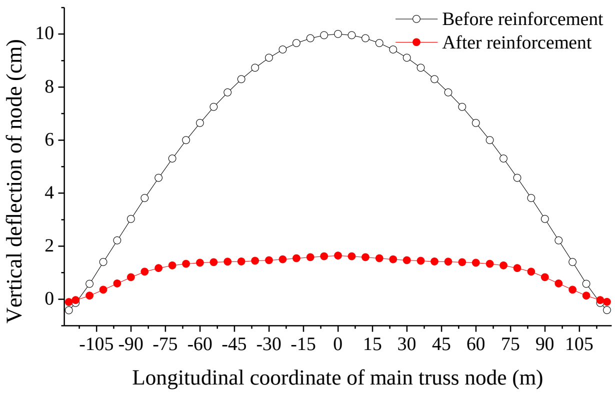

Fig.7 The vertical displacement of the main girder under the action of constant load

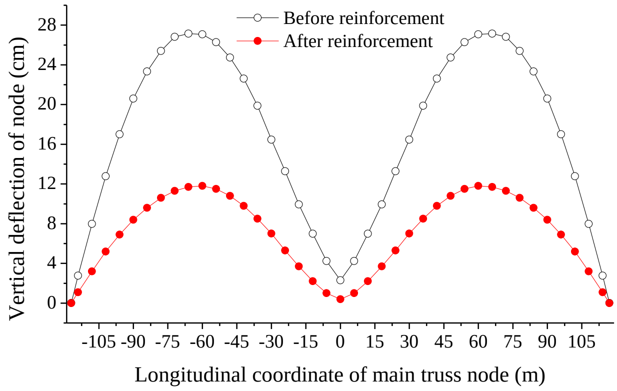

Fig.8 The maximum vertical displacement of main girder under the action of automobile loading

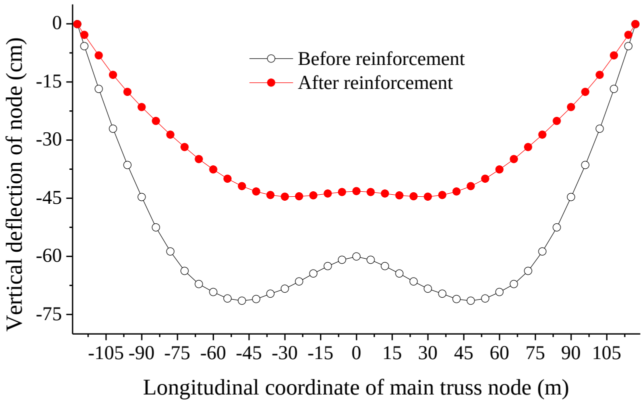

Fig.9 The minimum vertical displacement of main girder under the action of automobile loading

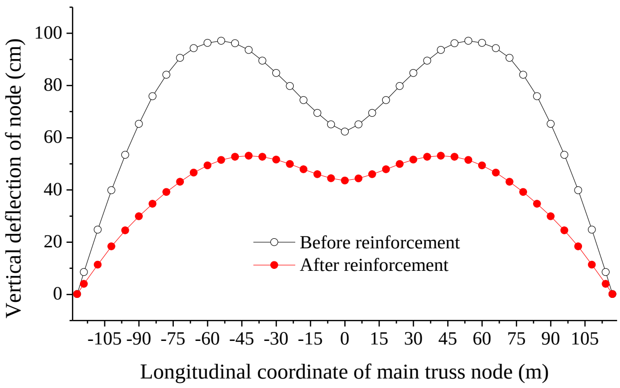

Fig.10 The sum of absolute value vertical displacement of the main girder under the action of automobile loading

Fig.7 to Fig.10 shown that the stiffness has been improved significantly adding cable system to partic-ipate in the structure. The main girder vertical dis-placement has been significantly reduced under the action of dead load and vehicle. The maximum sum of the absolute value of deflection under the action of automobile loading after reinforcement is 53.1cm which is much less than the 97.2cm before rein-forcement.

Adding the cable system to participate the struc-ture stress, structural stiffness has significantly im-proved. The sum about absolute value of the deflec-tion is bigger than 53.1cm and smaller than 97.2cm. It meets the requirement.

CONCLUSIONS

From the static analysis after reinforcement, the rein-forcement scheme is feasibility. The internal force, stress has larger decrease after reinforcement com-paring with the internal force, stress and stiffness in-dex before and after reinforcement. The stiffness of the structure also has a larger increase. But the stiff-ness of the structure also has a larger increase. And the key to solve the problem lies in the suspension cable force optimization. Reasonable cable force dis-tribution will lead to a more reasonable result. Be-lieve this reinforcement method will serve as a refer-ence for the same type of bridge reinforcement.

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