Research on the Suspender Replacement Process of Arch Bridge Based on the Measured Displacement Correction

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ABSTRACT The simplified method of arch bridge suspender replacement scheme based on the measured displacement correction is proposed in order to ensure the safety of the arch bridge suspender replacement process based on the pocket hanging method. Firstly, each group of replacement suspenders is separated from the pocket hanging system regardless of the constraint effect of the bridge deck on the suspenders, and the force analysis is carried out to obtain the displacement of the bridge deck under different cases; Then, the modified coefficient is obtained by using the measured displacement at the lower end of each suspender, and the modified coefficient is used to modify the displacement of the bridge deck, so that the calculation result can be applied to the case where the stiffness of the bridge deck cannot be ignored; Finally, the correctness of the method in this paper is verified by applying it to practical engineering. It can be concluded that the proposed method is simple, easy to operate and has high precision, which can be used in the removal of arch bridge suspenders through the verification results.

INDEX TERMS Arch bridge, displacement control, pocket hanging, suspender replacement.

I. INTRODUCTION

There are many categorical forms of bridges in the world, currently arch bridges are highly competitive due to their advantages of large span capacity, graceful shape and reasonable structural stress [1]–[3]. According to the latest statistics, more than 600 arch bridges have been built in China. However, both the half-through and through arch bridge need to transfer the load through the suspenders. Within components of a suspender arch bridge, suspenders transmit wind or live loads on the deck to the main rib, which are then transmitted to the earth [4]. suspender safety is directly related to the safety of the whole bridge [5]–[7].

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The suspender is often designed as a replaceable member with a design life of 20-30 years. However, the suspender is in a complex environment, which not only bears the constant load (dead weight of the structure), but also bears the alternating load (temperature, vehicle, wind load, etc.), and it is exposed to the corrosive environment such as humidity, high chloride ion, high and low temperature variation at the same time. As a result, the service life of the suspender (3-16 years) is far less than the designed life [8]. Therefore, suspender replacement is a very common work in this type of bridge maintenance. At present, more than 30 arch bridges in China have been involved in suspender replacement [9]. It can be expected that, there will be more and more suspenders involved in the replacement with the extension of service period. The commonly used methods of suspender

R. Lan *et al.*: Research on the Suspender Replacement Process of Arch Bridge Based on the Measured Displacement Correction

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replacement are temporary support method, temporary suspender method and pocket hanging method. Among them, the method of pocket hanging method is the most widely used because of its clear system conversion, reasonable structural stress and without blocking traffic.

Hossain and Sluszka [10] summed up a Suspender replacement progress for the suspension bridge earlier. Sun *et al.* [11] proposed a replacement method using temporary suspenders and performed field implementation of suspender replacement for a suspension. Taking Tianjin Yonghe bridge, for example, the finite element method is adopted by Yao *et al.* [12] to simulate each stages of suspender replacement process, the dates of tension, the alignment of main beam and the change of stress before and after suspender replacement are compared and analyzed. A sensitivity analysis was applied to assess the variations of force and deflection in the Sutong Bridge, China [13]. Based on the analysis results, replacing one suspender from the side span and replacing four Suspenders asymmetrically was recommended, and a replacement sequence running from the shortest suspender to longest suspender proved to be optimal. Sun *et al.* [14] used Kalman's filtering method in the construction control for suspender replacement combined with the suspender replacement project of Jiao-Ping Du suspender-stayed bridge. The results showed that the suspender tension of the cable-stayed bridge was 2926kN littler than the design suspender tension after changing the suspender of this bridge. Brown [15] describes the effort to replace all 72 of the stay Suspenders of the Hale Boggs Memorial Bridge.

Suspenders replacement works are highly technical works requiring special equipment, technology and engineering at all stages of the operation [16]. The structural response should be controlled within a reasonable range in the whole process of suspender replacement, and the internal force and linear deviation caused by the suspender replacement should be reduced as much as possible, so as to ensure that the structure will not crack due to excessive deformation, thus leading to the reduction of bearing capacity. Among them, the accurate control of displacement is particularly critical, which is often controlled within a reasonable range, and other response quantities (internal force, stress, etc.) can be controlled within the appropriate range.

According to the existing research, the process of suspender replacement is mainly simulated by finite element method (FEM), which mainly has the following two problems:

a) it is troublesome to simulate the replacement process of suspender, which requires high requirements for engineers and technicians. Due to the problems of system conversion involved in the process, the correct results can't be obtained if it is handled improperly in the process of finite element simulation;

b) It takes a lot of time to simulate the replacement process of suspender. The process of suspender replacement involves geometric nonlinearity, which makes the single simulation time longer. In addition, the total calculation time will increase due to the actual operation process often needs multiple trial calculations for the cutting area of the old suspender and the tension force can't be determined accurately in advance.

To sum up, the existing calculation method of suspender replacement can't meet the actual engineering requirements. Therefore, it is necessary to find a practical and convenient calculation method. This paper will put forward a calculation method of arch bridge suspender replacement based on measured displacement correction, which not only has the advantages of simple calculation and high accuracy, but also has the advantages of fast calculation.

The contributions in this paper are three folds: 1) The simplified calculation equation of suspender replacement is formed without considering the constraint effect of bridge deck on suspenders; 2) the modified coefficient is introduced, and the simplified equation is modified to consider the constraint effect of the bridge deck on the suspenders; 3) this method is applied to the replacement of suspenders in an arch bridge to verify the correctness and practicability of this method.

The structure of this paper is organized as follows: Section 2 describe the theoretical framework, including the construction methods and process of suspender replacement as well as the simplified suspender replacement process model. Section 3 presents the simulation results to validate the proposed approach. Section 4 concludes and summarizes the work.

II. THEORETICAL FRAMEWORK
A. CONSTRUCTION METHOD AND PROCESS OF SUSPENDER REPLACEMENT

The pocket hanging method to replace the suspender is to use the wire rope, that is, the suspender beam in the place of the suspender to be replaced will be directly pocket hanging on the arch rib, then cut the wire in batches, the pocket hanging system should be supplemental tensioned every time the wire is cut in order to balance the decrease of the suspender force of the suspender to be replaced. The new suspenders are installed, then tensioned, and unloaded at different stages until the internal forces of the suspenders are unloaded after removing the suspenders to be replaced. Pocket hanging method is a kind of suspender replacement method which can actively change and improve the force of the structure. The principle of "displacement control is the main, suspender force control is the auxiliary" is followed in the process of suspender replacement, the suspender force can be within a reasonable range when the displacement is controlled within a reasonable range. The suspender replacement flow based on the pocket hanging method is shown in Fig. 1.

The replacement of suspenders is the process of removing old suspenders and installing new suspenders, and there are two system conversions in the replacement process. The first system transformation is that the force in the old suspender
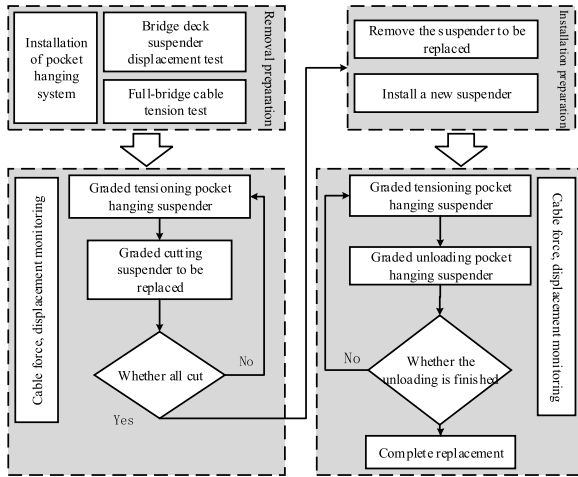
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R. Lan *et al.*: Research on the Suspender Replacement Process of Arch Bridge Based on the Measured Displacement Correction

FIGURE 1. The suspender replacement process based on the pocket hanging method.
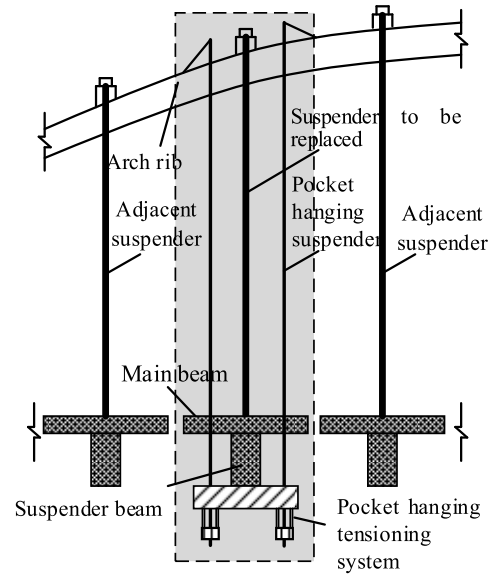
is transferred to the temporary pocket hanging system by the tension of the temporary pocket hanging system and the cutting of the old suspender to complete the removing of the old suspender. The second system transformation is that the suspender force in the temporary pocket hanging system is transferred to the new suspender by the tensioning of the new suspenders and the unloading of the temporary pocket hanging system, and the final new suspenders replace all the functions of the old suspenders.

B. SIMPLIFIED SUSPENDER REPLACEMENT PROCESS MODEL

1) MODEL SIMPLIFICATION

The bridge deck of the half-through and through arch bridge mostly adopts the beam-slab structure in the early stage, the cross beam is mainly used to bear the load, and the longitudinal beam is not set, that is, the construction technology of the first beam and then the direct bridge deck is adopted. The stress of the technological structure is clear, and the construction is convenient. The suspender replacement of this type of structure is shown in Fig. 2.

The bending stiffness of the bridge deck is small in this structure with longitudinal connection, further, the constraint on the lower end of suspender replacement is limited in the process of suspender replacement, therefore, it can be assumed that the bridge deck only acts on the beam with deadweight load, and does not provide the constraint effect. Therefore, it is possible to separate the old suspender and the pocket hanging system as a unit, such as the dotted portion in Fig. 2, when the lifting force of the pocket hanging system is equal to the reduced internal force of the old suspender, so that the displacement and internal force transformation of the pocket hanging suspender and the suspender to be replaced during the replacement process is more clear. The suspender replacement process will be simulated according to this unit.

FIGURE 2. Simplified suspender replacement diagram.

2) SUSPENDER REPLACEMENT PROCESS

Suppose the suspender force to be replaced is F, elastic modulus is E, section area is A, suspender length is L; As for temporary suspender: elastic modulus is E_d, area is A_d, suspender length is L_d. When the first pocket hanging force increment of temporary suspender is F_1, the suspender force of suspender to be replaced decreases ΔF_1. The height of ascending of the bridge deck system Δ_{1+} after the first pocket hanging [8] is as follows:

$$\Delta_{1+} = \frac{\Delta F_1 L}{EA} \tag{1}$$

The suspender to be replaced and the pocket hanging suspender form a new system after the first pocket hanging is completed. When a unit force is applied to the lower end of the system, the internal force of the suspender to be replaced increases to F_o, the internal force of the pocket hanging suspender increases to F_d, let the equivalent tensile stiffness of the equilibrium system is B_e^0. Based on force balance and displacement coordination, it has:

$$F_o + F_d = 1 \tag{2}$$
$$\frac{1 \cdot L}{B_e^0} = \frac{F_o L}{EA} = \frac{F_d L_d}{E_d A_d} \tag{3}$$

Through (2) and (3), there is

$$B_e^0 = \frac{L_d EA + E_d A_d L}{L_d} \tag{4}$$

When the suspender is cut for the first time, its area reduces delta ΔA_1, during the descent of the bridge deck system, the pocket hanging system takes part in the force of the system together, and the internal force of the old suspender and the pocket hanging system is rebalanced. Equivalent tensile

R. Lan *et al.*: Research on the Suspender Replacement Process of Arch Bridge Based on the Measured Displacement Correction

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stiffness B_e^1 can be obtained according to (4), then one has

$$B_e^1 = \frac{L_d E (A - \Delta A_1) + E_d A_d L}{L_d} \quad (5)$$

After the first cutting of the suspender, the descent height of the deck system Δ_{1-} is

$$\Delta_{1-} = \frac{FL}{B_e^1} - \frac{FL}{B_e^0} \quad (6)$$

Substitute (4) and (5) into (6), it has

$$\Delta_{1-} = \frac{FLL_d}{L_d E (A - \Delta A_1) + E_d A_d L} - \frac{FLL_d}{L_d EA + E_d A_d L} \quad (7)$$

Internal force of pocket hanging suspender is

$$F_{d1} = \frac{\Delta_1 - E_d A_d}{L_d} \quad (8)$$

Analogizing later, after lifting the pocket hanging system for the n th time, the pocket hanging force increment is ΔF_n, the remaining area of the suspender to be replaced is $\left(A - \sum_{i=1}^{n-1} \Delta A_i\right)$, and the rise height of bridge deck system Δ_{n+} is

$$\Delta_{n+} = \frac{\Delta F_n L}{E \left(A - \sum_{i=1}^{n-1} \Delta A_i\right)} \quad (9)$$

After cutting the suspender for the n th time, the area of suspender to be replaced has been reduced by ΔA_n, and the fall height of bridge deck system Δ_{n-} is

$$\Delta_{n-} = \frac{FLL_d}{L_d E \left(A - \sum_{i=1}^{n} \Delta A_i\right) + E_d A_d L}$$
$$- \frac{FLL_d}{L_d E \left(A - \sum_{i=1}^{n-1} \Delta A_i\right) + E_d A_d L} \quad (10)$$

Internal force of the pocket hanging suspender F_{dn} can be obtained by

$$F_{dn} = \frac{\Delta_n - E_d A_d}{L_d} \quad (11)$$

According to (9) and (10), the cumulative displacement of the bridge deck can be obtained as

$$\Delta_{total, n*} = \begin{cases} \sum_{i=1}^{n} (\Delta A_{i+} + \Delta A_{i-}), & * = + \\ \sum_{i=1}^{n-1} (\Delta A_{i+} + \Delta A_{i-}) + \Delta A_{n+}, & * = - \end{cases} \quad (12)$$

For the installation of new suspenders, the stiffness of the suspenders is not involved in the installation process, therefore, the installation process is the same as the old suspenders in the removal of the pocket hanging process.

The previous section is a model formed under the assumption that the suspender replacement unit has no other external constraints, which is more accurate in the simulation of the bridge deck structure without the main beam. However, this kind of structure which does not set the main beam, forms the longitudinal mutual connection only through the relatively weak bridge deck, where the integrity is poor, and has been
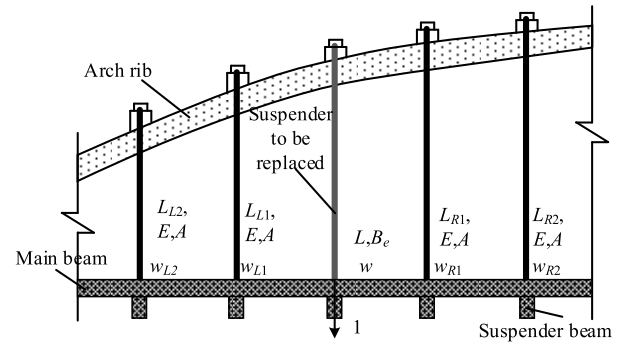

FIGURE 3. The displacement changes of bridge deck at the lower end of each suspender under the action of unit force.

gradually eliminated. At present, the commonly used structural form is the bridge deck grid beam, which often contains two main beams with large stiffness and multiple secondary main beams. At this time, the main beam to the suspender restraint effect is often very strong in the process of suspender replacement, and the main beam share the pocket hanging force even more than the change of the internal force of the suspender itself in the process of pocket hanging. Therefore, it is necessary to correct the lifting force. In practical engineering, the displacement of the bridge deck at the lower end of the suspender is easily and accurately obtained, while the change of the internal force of the suspender is directly related to the displacement of the bridge deck at the lower end of the suspender. For this reason, the bridge deck displacement at the lower end of the suspender is introduced to modify the model. Concretely, the correction coefficient K is introduced, which represents the proportion of the change of internal force of the suspender to be replaced and the internal force of the pocket hanging suspender in the internal force exerted by the pocket hanging system.

In order to calculate K, assuming a unit force is applied at the lower end of the suspender to be replaced, the displacement at the lower end of the suspender to be replaced is w, the displacement at the lower end of the suspender to be replaced is $w_{L1}, w_{L2}, \cdots, w_{L,nl}$ (where nl represents the total number of suspenders on the left side of the suspender to be replaced), and the displacement at the lower end of the right side of the suspender to be replaced is $w_{R1}, w_{R2}, \cdots, w_{R,nr}$ (where nr represents the total number of suspenders on the right side of the suspender to be replaced), as shown in Fig. 3, where L_* represents the length of the suspender, B_e is the equivalent stiffness of the suspender to be replaced and the pocket hanging suspender.

For suspenders to be replaced, according to Hooke's law, when the displacement increases w, the increment of suspender force ΔF is

$$\Delta F = \frac{wB_e}{L} \quad (13)$$

Let $B_e = kEA$, there is

$$\Delta F = \frac{wkEA}{L} \quad (14)$$

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R. Lan *et al.*: Research on the Suspender Replacement Process of Arch Bridge Based on the Measured Displacement Correction

Similarly, the internal force increment of other suspenders can be obtained, and the K can be calculated according to the balance principle of force as follows

$$K = \frac{wk/L}{\frac{wk}{L} + \sum_{i=1}^{nl} \frac{w_{Li}}{L_{Li}} + \sum_{i=1}^{nr} \frac{w_{Ri}}{L_{Ri}}} \quad (15)$$

It can be seen from the (15) that the K actually represents the ratio of k times the displacement per unit length of the suspender to be replaced to the sum of the displacement per unit length of all the suspender. Therefore, only arbitrary force is needed to be applied to the pocket hanging system in practical engineering, then test the displacement change of the lower end of each suspender, further, K can be obtained through (15).

The correction coefficient is used to modify the pocket hanging force, substitute the correction coefficient into (9) and (10), there is

$$\Delta_{n+} = \frac{K \Delta F_n L}{E\left(A - \sum_{i=1}^{n-1} \Delta A_i\right)} \quad (16)$$

$$\Delta_{n-} = \frac{KFLL_d}{L_d E\left(A - \sum_{i=1}^{n} \Delta A_i\right) + E_d A_d L}$$
$$- \frac{KFLL_d}{L_d E\left(A - \sum_{i=1}^{n-1} \Delta A_i\right) + E_d A_d L} \quad (17)$$

It is worth noting that the section stiffness of the suspenders to be replaced is constantly changing during the construction process, resulting in change of equivalent stiffness B_e. However, it is only necessary to measure the displacement of all suspenders once, combined with the cutting area of the suspenders to be replaced in different construction stages, further, K under different construction stages can be obtained. The equivalent stiffness is unchanged in the process of installing the new suspender because the suspender stiffness has not changed.

From (16) and (17), one could see the displacement of the deck is related to many parameters especially K. However, in the actual construction process, if the deviation between the measured value and the calculated value is too large, it can be corrected by increasing the actual displacement measurement and updating K, so as to reduce the further increase of the error.

III. EXPERIMENT

The super large bridge of a highway is a half-through concrete filled steel tubular truss arch bridge, as shown in Fig.4. The main bridge adopts a single hole half-through concrete filled steel tubular truss arch bridge with clear span 190m, the arch rib section is 4.3m high, 2.0m wide. The cross section of the main beam consists of the π-shape bridge deck on both sides and the 10 hollow slab main beam in the middle, as shown in Fig. 5. There are 27 suspenders on one side of the bridge with a distance of 5.1m, and the suspender is 85φ7 parallel wires suspender. The bridge was opened to operation in December 2003, it was found that some of

FIGURE 4. Bridge elevation.

TABLE 1. The removal grade of the suspender to be replaced.

Case	1+	1-	2+	2-	3+	3-	4+	4-	5+	5-	6+	6-
ΔF_i ($F\%$)	10%		30%		50%		70%		90%		100%	
Controlling tension (kN)	94		282		470		658		846		940	
ΔA_i	0%	35%	-	25%	-	15%	-	15%	-	5%	-	5%

the suspender sheaths were damaged, the anchor head has water accumulation, and the suspender force deviation of the suspender was large during the regular inspection.

The suspenders of the bridge ware replaced in 2016 using the method of pocket hanging method by regarding upper and lower suspenders as a pair, which consists of two φ60mm steel core wire ropes (6 × 37S + IWR), two I36b joist steel pocket hanging beam, four groups of 6φ15.2 steel strand pocket hanging suspenders, four sets of tension jacks and QMV.DHM15-6 low retracting anchor belt locking anchors, etc.

This method is verified by taking the No.14 suspender in upstream as an example. The elastic modulus of the old suspender is 205 GPa, the calculated length of the suspender is 24.098m, the designed suspender tension is 940 kN, and the measured suspender force is 853 kN; The pocket hanging system is 6φ15.2 steel frame wire, the length of the pocket hanging wire is 21.4m, four φ64 and arch ribs are used to bind the steel strand above the steel strand after the transfer from the wire rope to the steel strand docking device and the length of the wire rope is 7.8m. Considering the safety and construction convenience of replacing the suspender, the method of replacing the suspender with unequal step length is adopted in this paper, the pocket hanging force is divided into 6 times tensioning, and the old suspender steel wire is cut in 6 batches. The lifting force working procedure. The pocket hanging force is used as the target suspender force according to the designed 940kN, and the removal grade of the suspender to be replaced is presented in Table 1.

The force of 100kN is applied to the pocket hanging system before the suspender is removed, and then the displacement of the bridge deck at the lower end of the suspender is tested by the total station instrument (as shown in Fig. 5), and the

R. Lan et al.: Research on the Suspender Replacement Process of Arch Bridge Based on the Measured Displacement Correction

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TABLE 2. Bridge deck displacement at lower end of different suspender.

| Suspender number	Length (mm)	Displacement (mm)	Suspender number	Length (mm)	Displacement (mm)	Suspender number	Length (mm)	Displacement (mm)
1#	4656	-0.09	10#	22595	0.23	19#	21550	0.14
2#	7612	-0.12	11#	23407	0.34	20#	20271	0.05
3#	10323	-0.14	12#	23987	0.56	21#	18757	-0.02
4#	12791	-0.14	13#	24334	1.04	22#	17006	-0.08
5#	15018	-0.12	14#	24450	1.60	23#	15018	-0.12
6#	17006	-0.08	15#	24334	1.04	24#	12791	-0.14
7#	18757	-0.02	16#	23987	0.56	25#	10323	-0.14
8#	20271	0.05	17#	23407	0.34	26#	7612	-0.12
9#	21550	0.14	18#	22595	0.23	27#	4656	-0.09
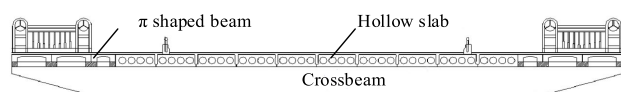
FIGURE 5. Cross section of main beam.

change of the bridge deck displacement at the lower end of each suspender is obtained as exhibited in Table 2.

When the constraint effect of the main beam on the suspender replacement unit is ignored, the displacement of bridge deck at the lower end of suspender to be replaced under different cases is calculated by the (9) and (11), as shown in Line 3 in Table 3. It can be seen that it is much larger than the measured displacement by comparing with the measured displacement, which is mainly because the longitudinal connection of the bridge consists of π-shaped bridge on both sides and a hollow slab in the middle, therefore the constraint of the main beam on the suspender replacement unit cannot be ignored.

When the correction coefficient is considered, the displacement of the bridge deck at the lower end of the suspender to be replaced under different cases are calculated by the (16) and (17), as provided in Line 3 in Table 3. By comparison, the corrected displacement is very close to the measured displacement, and it is proved that the removal of arch bridge suspenders based on the corrected measured displacement is accurate.

The measured and calculated values of the bridge deck displacement at the lower end of the suspender during the installation of the new suspender are shown in Fig. 9, from which we can be seen that the displacement of the new suspender in installation process calculated by the revised calculation is very close to the measured results, same as process suspender removal, which verifies that the proposed method can be used in the new suspender installation process.

TABLE 3. The calculation result of displacement change of bridge deck.

Case	The measured displacement (mm)	Pre-correction displacement (mm)	Corrected displacement (mm)
1+	1.8	3.55	1.95
1-	-0.21	-0.33	-0.18
2+	1.5	3.09	1.7
2-	0.01	0.02	0.01
3+	2.1	4.24	2.33
3-	0.11	0.16	0.09
4+	1.7	3.38	1.86
4-	-0.41	-0.68	-0.37
5+	1.3	2.56	1.41
5-	0.56	0.95	0.52
6+	1.45	2.98	1.64
6-	0.8	1.2	0.66

TABLE 4. Materials of the modal.

Material type	Applicable parts	Modulus of elasticity / kN/m^2	Bulk density / kN/m^3
16Mn	Arch rib	2.10e8	76.98
OVMLZM7-55 III	Old suspenders	2.05e8	78.5
Finished Deformed Bar	Temporary suspenders	2.06e8	100.7
OVMLZM7-55 IV	New suspenders	2.05e8	78.5
C50	Deck	3.45e7	26
Q345	Main girders and crossbeams	2.06e8	100.7

FIGURE 6. Bridge deck displacement test at lower end of suspender.

In order to verify the practicability, convenience and accuracy of the proposed method, the process of suspender replacement is also simulated by FEM. The three-dimensional finite element model is formed in Midas Civil (2018) as shown in Fig.10. the whole model consisted of 1786 nodal points, 80 truss elements, 2735 beam elements and 370 plate elements. The suspenders are represented with truss elements, the deck is described by plate elements while others are represented with beam elements. The materials of the modal are listed in Table 4.

In the process of suspender replacement, there are two important steps: old suspender cutting and new suspender installation. The finite element simulation is as follows:
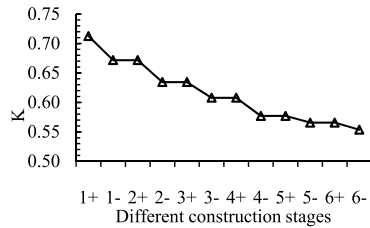
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R. Lan *et al.*: Research on the Suspender Replacement Process of Arch Bridge Based on the Measured Displacement Correction

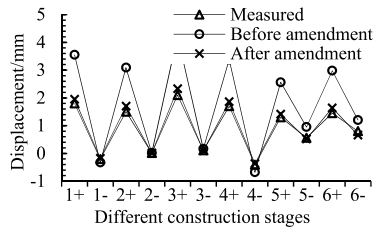**FIGURE 7.** The correction coefficients under different cases.

FIGURE 8. Comparison of bridge deck displacement at the lower end of the suspender under different cases in the removal of the suspenders.
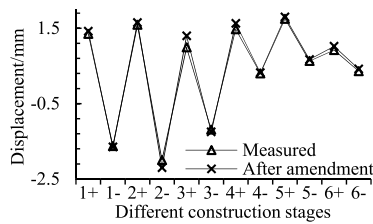

FIGURE 9. Comparison of bridge deck displacement at the lower end of the suspender under different cases when the new suspender is installed.
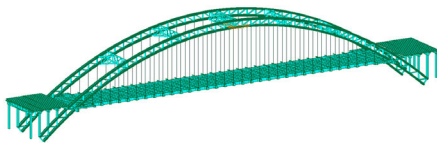

FIGURE 10. Finite element model.

(1) In the FEM, the cutting of the old suspender actually involves the simulation of the geometric nonlinearity. In order to simplify, several repeated elements are usually established at the same position of the old suspender. These elements have the same parameters except the cross-sectional area. The cutting process of the old suspender is simulated by activating the suspender corresponding to the area of the construction stage in different construction stages and passivating the suspender of the previous construction stage. It is also important to note that the element needs to be activated along the initial tangential displacement of the member.

(2) It is relatively easy to simulate the process of the installation of the new suspender because it does not involve the geometric nonlinearity of the structure. However, the method of external force replacement is needed when the temporary suspender force is transformed into the new suspender force,

Taking the 14# suspender in the upstream as an example, there are 24 working conditions for the removal of the old boom and the installation of the new boom, as shown in Table 4.

TABLE 5. Working condition table of 14 suspender replacement process.

| Working condition	Demolition of old suspender	working condition	Installation of new suspender
1+	Temporary suspender tensioning 10%	1+	New suspender tensioning 10%
1-	Old suspender cutting 35%	1-	Temporary suspender unloading 10%
2+	Temporary suspender tensioning 30%	2+	New suspender tensioning30%
2-	Old suspender cutting 60%	2-	Temporary suspender unloading 30%
3+	Temporary suspender tensioning 50%	3+	New suspender tensioning 50%
3-	Old suspender cutting 75%	3-	Temporary suspender unloading 50%
4+	Temporary suspender tensioning 70%	4+	New suspender tensioning 70%
4-	Old suspender cutting 90%	4-	Temporary suspender unloading 70%
5+	Temporary suspender tensioning 90%	5+	New suspender tensioning 90%
5-	Old suspender cutting 95%	5-	Temporary suspender unloading 90%
6+	Temporary suspender tensioning 100%	6+	New suspender tensioning 100%
6-	Old suspender cutting 100%	6-	Temporary suspender unloading 100%
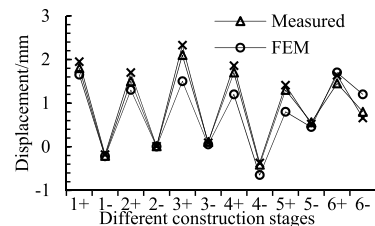
FIGURE 11. Comparison of bridge deck displacement at the lower end of suspender under different working conditions during suspender removal.

The finite element simulation is carried out on the T4900d-21 Lenovo microcomputer: The operating system is windows 10 64 bit; The processor is i7-7700, 4 cores, 8 threads, 8 MB LEVEL 3 cache, and the highest frequency is 4.5GHz; The memory model is DDR4, the capacity is 8.00GB; the video card model is NVIDIA GeForce GT 730, capacity is 2048MB, and the RAMDAC frequency is 400MHz.

The calculation results of the bridge deck displacement at the lower end of the suspender under different working conditions during the removal of the suspender and the installation of the new suspender are shown in tables 5 and 6 respectively, and the corresponding comparison results are shown in Fig. 11 and Fig. 12.

R. Lan *et al.*: Research on the Suspender Replacement Process of Arch Bridge Based on the Measured Displacement Correction

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TABLE 6. Calculation results of bridge deck displacement at the lower end of suspender under different working conditions during suspender removal.

Working condition	1+	1-	2+	2-	3+	3-	4+	4-	5+	5-	6+	6-
Measured	1.8	-0.21	1.5	0.01	2.1	0.11	1.7	-0.41	1.3	0.56	1.45	0.8
FEM	1.65	-0.22	1.3	0.005	1.5	0.05	1.2	-0.65	0.8	0.45	1.7	1.2
FMD	-8	5	-13	-50	-29	-55	-29	59	-38	-20	17	50
Present paper	1.95	-0.18	1.7	0.01	2.33	0.09	1.86	-0.37	1.41	0.52	1.64	0.66
PMD	8	-14	13	0	11	-18	9	-10	8	-7	13	-18

Note: FMD = (FEM- Measured)/ Measured*100, PMD=(Present paper-Measured)/Measured*100.

TABLE 7. Calculation results of bridge deck displacement at the lower end of suspender under different working conditions in new suspender installation.

Working condition	1+	1-	2+	2-	3+	3-	4+	4-	5+	5-	6+	6-
Measured	1.35	-1.63	1.59	-2	0.99	-1.19	1.47	0.3	1.75	0.63	0.92	0.36
FEM	1.2	-1.58	1.3	-1.5	0.75	-0.89	1.3	0.2	1.5	0.4	0.84	0.26
FMD	-11	-3	-18	-25	-24	-25	-12	-33	-14	-37	-9	-28
Present paper	1.42	-1.65	1.65	-2.2	1.3	-1.25	1.63	0.32	1.8	0.67	1.02	0.42
PMD	5	1	4	10	31	5	11	7	3	6	11	17

Through the calculation results, it can be seen that:

(1) The trend of the finite element calculation results is basically consistent with the measured results, but the deviation between measured and FEM is still large. The main reason is that there are some differences in material parameters and boundary conditions between the finite element model and the actual structure. However, if one wants to make the parameters in finite element model consistent with the actual structural, a lot of field tests and calculation work are needed to do, so FEM is not conducive to engineering application in simulating the suspender replacement process.
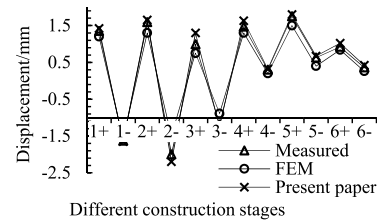

FIGURE 12. Comparison of bridge deck displacement at the lower end of suspender under different working conditions during installation of new suspender.

(2) It takes 55 minutes and 25 minutes respectively to remove the suspender and install the new suspender by finite element simulation. However, only a small amount of calculation time is needed to use the proposed method. At the same time, the results calculated by this method are closer to the measured values than the FEM. It is proved that the proposed method is fast and accurate.

IV. CONCLUSION

In view of the difficulty in simulation calculation of suspender replacement of arch bridge, this paper puts forward an innovative method of suspender replacement based on measured displacement correction. Firstly, the simplified calculation equation of suspender replacement is formed without considering the constraint effect of bridge deck on suspenders; Secondly, the modified coefficient is introduced, and the simplified equation is modified to consider the constraint effect of the bridge deck on the suspenders; Finally, this method is applied to the replacement of suspenders in an arch bridge to verify the correctness and practicability of this method. The main conclusions are drawn as follows.

(1) In order to establish the mathematical model of suspender replacement more easily and clearly, an ideal model is established under the condition of neglecting the influence of bridge deck to replace suspender. The model can be directly used in engineering practice with weak longitudinal connection of bridge deck;

(2) On the basis of the idealized mathematical model, the correction coefficient formed by the measured displacement data is introduced, thus a more accurate theoretical model for the suspender replacement process is obtained. Through the suspender replacement project of an arch bridge, it is verified that the model is accurate enough and can be used in engineering practice with strong longitudinal connection of bridge deck;

(3) Compared with the traditional calculation method, the method proposed in this paper is not only more accurate, but also more efficient. It solves the problem that the traditional method needs higher theoretical level of engineering technicians and the problem that the desired control results cannot be obtained quickly. It is not only suitable for weak longitudinal connection of bridge girder, but also suitable for strong longitudinal connection of main beam, so it has wide applicability.

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R. Lan *et al.*: Research on the Suspender Replacement Process of Arch Bridge Based on the Measured Displacement Correction

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APPENDIX

Table for nomenclature

Symbol	Denote
F	suspender force
E	suspender elastic modulus
A	section area
L	suspender length
E_d	elastic modulus for temporary suspender
A_d	section area for temporary suspender
L_d	suspender length for temporary suspender
F_1	first pocket hanging force increment for temporary suspender
B_e^0	equivalent tensile stiffness of the equilibrium system
F_{dn}	internal force of the pocket hanging suspender
$\Delta_{total,n*}$	cumulative displacement of the bridge deck
K	correction coefficient

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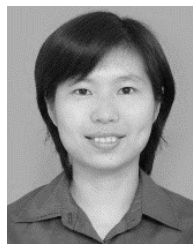
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