VACUUM-AIDED CONCRETE CASTING TECHNIQUE FOR CFST ARCH BRIDGES: EXPERIMENTAL INVESTIGATION AND PRACTICAL APPLICATIONS

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SUMMARY

To address the interfacial concrete separation problem of concrete-filled steel tube (CFST) arch bridges, 2 50m-long steel tube models were designed and fabricated for comparative tests, where the vacuum-aided grouting technique and the normal-pressure grouting procedure were employed respectively to cast the concrete in tubes. The ultrasonic detection method and the cutting inspection method were applied to the experimental concrete-filled tubes to verify the effectiveness of the vacuum-aided grouting technique, of which the working mechanism was also clarified. In turn the defects and the corresponding improving measures of the original vacuum-aided grouting technique were discussed. Finally the improved technique was applied in the construction of real bridge engineering, to actually realize full-process vacuum-aided grouting. The developed technique greatly reduces the interfacial concrete separation areas as well as the long-term separation distances, and effectively insures the compactness of the cast concrete in the steel tubes. This technique has been patented and generalized to the construction of 3 super-span arch bridges.

Keywords: *Arch bridge, concrete filled steel tube, vacuum-aided, casting, construction.*

1. INTRODUCTION

The interfacial concrete separation problem in the tubes of CFST arch bridges has baffled the people for many years, and consequently adversely affected the forward development of CFST arch bridges to some extent. Therefore, how to tackle this problem and reduce the separation distress as far as possible, becomes crucial and urgent. The causes for the separation involve such factors as the construction procedure, the concrete material property, temperature effect and concrete creep & shrinkage, among which the construction procedure is the dominant one [1]. At present the popular procedure for concrete filling in steel tubes is of a pushing-up style. After the concrete in a steel tube is pushed up to a certain height, within the range where the tube elevation angle is less than the air escape angle, air is liable to be enclosed in the concrete to form cavities by the concrete free surface waves or surges near the steel tube crown wall; furthermore, at the completion of concrete pumping, concrete bleeding starts to go up and collect into those cavities, meanwhile air bubbles continually move up to the tube crown to form more cavities. The bleeding cavities or air cavities introduce initial separation between the concrete and the steel tube wall, which accounts for the trouble root hidden in the construction procedure. Accordingly, to reduce and even eliminate the concrete separation in steel tubes, the first issue is to reduce and even eliminate the air cavities in the tubes near the completion of concrete pumping, then rationally comes the idea of the vuccum-aided grouting technique for concrete construction in tubes. As is shown in Fig. 1, the Hejiang Changjiang River 1st Bridge with a 530m main span, is the largest-span CFST arch bridge in the world. Each of the main arch rib chord tubes in this bridge has a diameter up to 1.3 m and a concrete volume of 800 m^3. How to implement a reliable construction procedure for concrete casting in the huge tubes, insure high compactness and reduce long-term concrete separation as far as possible, form one of the core technical problems for the construction of this bridge as well as other CFST arch bridges with similar-level large spans up to 500 m. For this purpose the following tests were designed and conducted.

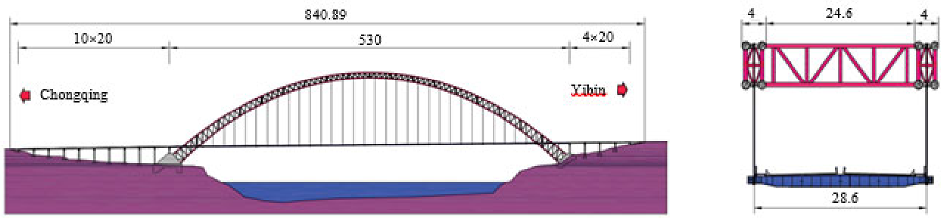


Fig. 1. *The Hejiang Changjiang River 1st Bridge (unit: m).*

2. TESTING PROGRAM

Currently, for super-span CFST arch bridges, inner flanges are usually used to connect the rib segments during hoisting and assembling of the arch ribs. The inner flanges bring convenience for construction on the one hand, but cause disadvantages on the other hand. Empirically, the interfacial concrete separation is mostly observed around the arch crown part and the inner flange connection part of rib tubes in CFST arch bridges. Therefore these 2 parts were chosen for comparative observation in the tests done respectively with the vacuum-aided grouting technique and the normal-pressure grouting procedure, and the ultrasonic detection method, the hammering method and the cutting inspection method were employed to judge if the vacuum-aided grouting technique was better than the normal-pressure one in the control of concrete separation. In the tests 2 steel tubes with the same diameter of 700mm and the same length of 50m were intended to simulate the crown part of a real arch rib, and 3 inner flanges were arranged in each tube, as were shown in Fig. 2. The vacuum grouting machine for prestressed concrete construction was used for the vacuum pumping test, and the 90-type high-pressure pump was used for the transport of testing concrete. The testing equipment setup was shown in Fig. 3 [2]. During the operation test the vacuum was between -0.07MPa and -0.09MPa. The testing concrete was in the same proportion with the C60 concrete used for the real bridge. A detailed scheme was made before the tests to insure the testing operation and the casting procedure were identical to those in the real bridge construction.

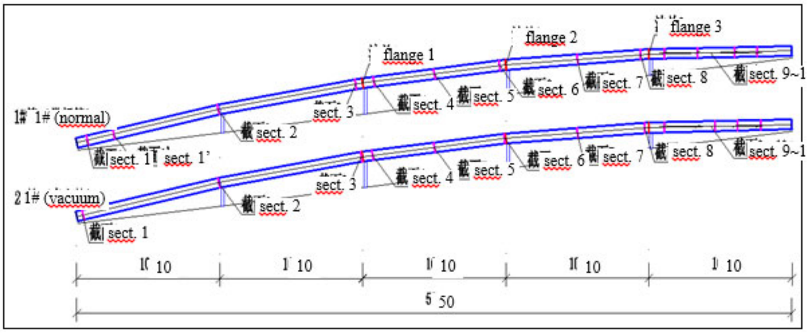


Fig. 2. Sizes of the testing arch rib tubes (unit: m).

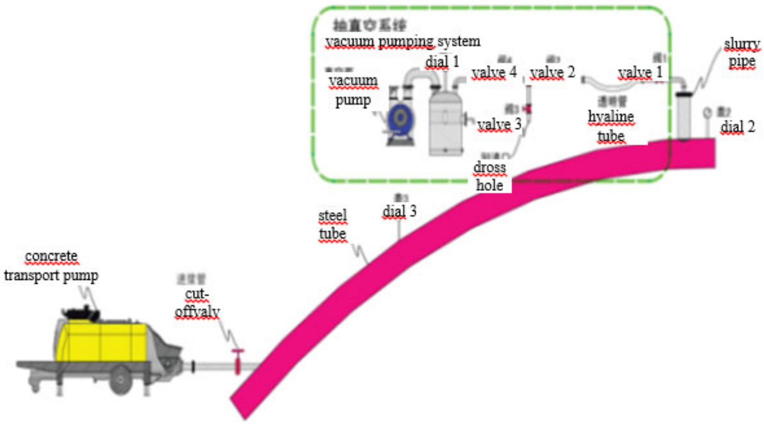


Fig. 3. The equipment setup for the vaccum-aided grouting test.

3. ANALYSIS OF TEST RESULTS

3.1. Results of ultrasonic detection

3.1.1. Precedents of ultrasonic detection

According to literatures [4-8], detection of the concrete filling compactness in steel tubes had been practicably conducted with the combined hammering and ultrasonic method, which was then applied here to probe and judge the concrete casting quality in the testing steel tubes.

3.1.2. Cross sections and channels for detection

After completion of the concrete casting, at different concrete ages, the concrete-filled steel tubes were detected at chosen cross sections shown in Fig. 2. Arrangement of the detection channels on a tube cross section was shown in Fig. 4.

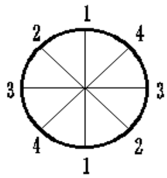
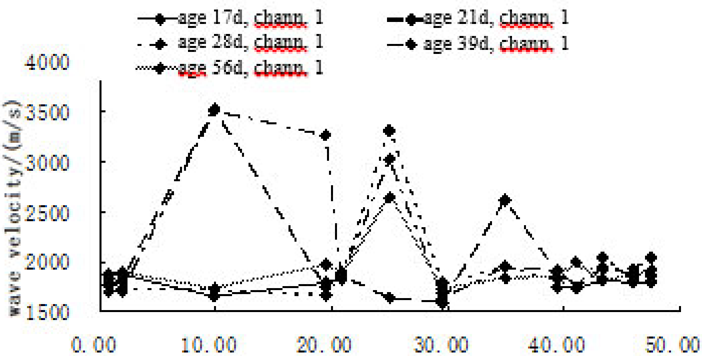


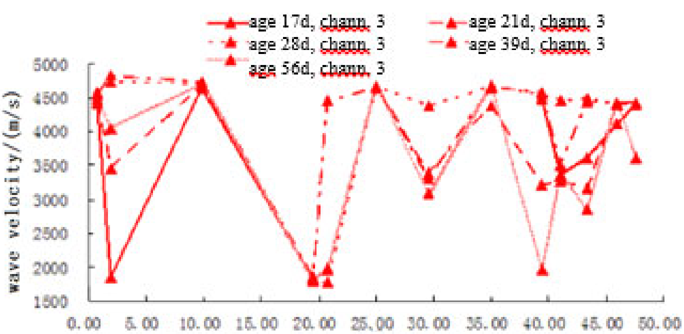
Fig. 4. The ultrasonic detection channels.

3.1.3. Detection results

Detection results of the 1# concrete-filled steel tube cast with the normal-pressure grouting procedure were shown in Fig. 5, and those of the 2# cast with the vacuum-aided grouting technique in Fig. 6. The detected condition along channel 2 or 4 were between those along 1 and 3. As for the ultrasonic method, the larger the wave velocity is, the higher compactness the concrete filling has.

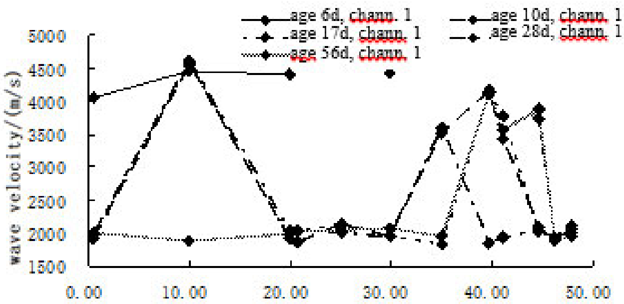


a) horizontal distance from the skewback [m] – channel 1.

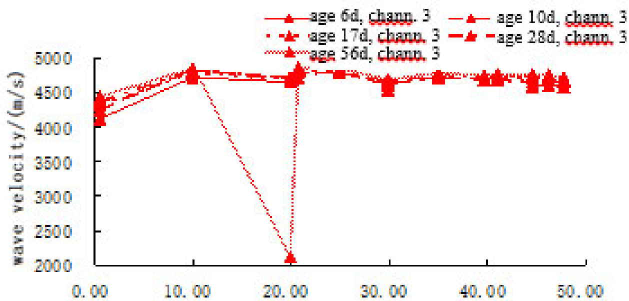


b) horizontal distance from the skewback [m] - channel 3.

Fig. 5. *Ultrasonic detection results of the 1# testing tube with the normal-pressure procedure.*



a) horizontal distance from the skewback [m] - channel 1.



b) horizontal distance from the skewback [m] - channel 3.

Fig. 6. *Ultrasonic detection results of the 2# testing tube with the vacuum-aided technique.*

3.1.4. Comparison of the ultrasonic results

General situation

1) Comparison of the results along corresponding channels between Fig. 5 and Fig. 6 indicates that, the data from the 2# testing tube are better than those from the 1#, especially along channel 3 which is free from gravity effect and gives more apparent wave velocities mostly over 4000 m/s, proving the vacuum-aided technique yields better effects than the normal pressure procedure. Statistically, as the data at age 17d tell, for the 2# testing tube with the vacuum-aided technique, 73% of all the cross-section detection channels give wave velocities over 4000 m/s, while for the 1# testing tube with the normal pressure procedure the corresponding percentage is only 18%. That also proves the superiority of the vacuum-aided technique.

2) Fig. 6 shows that, according to the detection results of age 6d from the 2# tube (those from the 1# were not obtained for some reason), over 90% of all the cross-section detection channels give wave velocities over 4000m/s, which means the vacuum-aided technique insures full filling of concrete in the steel tube and then yields satisfactory concrete compactness. After age 6d, the

gradual emergence of cavities and interfacial separation in the concrete-filled tube shall be attributed to concrete shrinkage or some other factors.

The situation around the inner flanges.

The detection results of the 2 testing tubes indicate that, at the 20m (where a inner flange lies) points of both the testing tubes, the concrete casting quality is generally poorer than that at other points without flanges. For the 2# testing tube with the vacuum-aided technique, although the wave velocities along all the detection channels around the inner flanges are beyond 4000m/s at age 6d, meaning full concrete filling in the tube during construction with the vacuum-aided technique, but those velocities fall down to 2000m/s at age 56d, proving the negative effects of the flanges on the long-term concrete compactness. During the later practical construction this fact shall receive enough attention and additional vibration devices shall be considered around the flanges.

3.2. Results of steel tube cutting inspection

3.2.1. General introduction

The 1# tube with the normal pressure procedure:

After cutting open of the steel tube, the exposed concrete body was fractured into 39 segments due to transport, then the segments was numbered for convenience. Visual inspection was made on the following typical segments: segment 1-9 at the 9 m (the horizontal distance from the lowest point of the tube, the same below) point of the tube, with local small voids; segment 1-20 at the 21 m point, with pits and local water/air passages; segment 1-36 at the 38m point, without defects; segment 1-37 at the 38.5 m point, with local concrete loosening; segment 1-38 at the 42.5 m point, with local interfacial separation of 70 cm × 10 cm sizes, shown in Fig. 7; segment 1-39 at the 44.7 m point, the last one, with local concrete loosening.

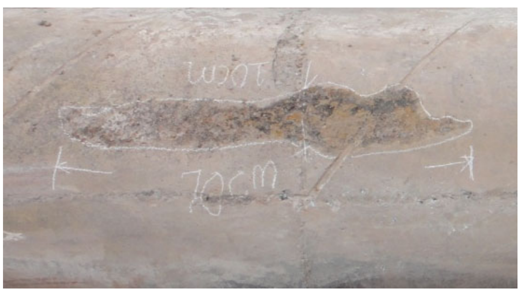


Fig. 7. *The local interfacial separation on segment 1-3.*

The 2# tube with the vacuum-aided technique:

After cutting open of the steel tube the exposed concrete body was fractured into 38 segments to be numbered, among which the following typical ones were visually inspected: segment 2-9 at the 10 m point, with a water/air passage of a 10mm width and a 1mm depth; segment 2-26 at the 30 m point, with a widening water/air passage of

10mm ~ 20 mm widths and a 1mm depth, shown in Fig. 8; segment 2-33 at the 38 m point, with a water/air passage of a 20 mm width and a 4mm depth; segment 2-37 at the 47.4 m point, with a widening water/air passage of 85 mm ~ 160 mm widths and a 10 mm depth; segment 2-38 at the 49 m point, the last one, with a water/air passage of a 180 mm width and a 10 mm depth.

Fig. 8. *The apparent water/air passage on segment 2-26.*

3.2.2. Mechanism analysis for the vacuum-aided grouting technique

1) Overall, the comparison of the cutting inspection results between the 1# and 2# tubes shows, within the 0 m ~ 38 m range (correponding to segments 1-1 to 1-36 of the 1# tube or segments 2-1 to 2-33 of the 2#) of the 50 m tube length, the appearance of the concrete segments from the 2# tube is far better than that from the 1#; within the 38m ~ 50m range, the results from the 2 tubes respectively have some defects: for the 1# tube 1 interfacial separation exists on segment 1-38 and 2 concrete loosening areas occur on segments 1-37 and 1-39, while for the 2# tube wider and deeper water/air passages occur.

2) In the crown part (from segment 2-23 at the 27 m point up) of the 2# tube with the vacuum-aided technique exist obvious through water/air passages, while in the corresponding part of the 1# tube with the normal pressure procedure exist some discontinuous water/air passages. That accounts for the better concrete casting effects of the vacuum-aided technique. The through water/air passages can siphon the enclosed air away from upper space of the steel tube, thereby avoid the local water/air collection and in turn the induced intractable local hidden defects such as small pores (as occurred to segment 1-9), local interfacial separation (as occurred to segment 1-38) and even local severe concrete loosening (as occurred to segment 1-39), etc. Accordingly, the mechanism of the vacuum-aided grouting technique can be made clear as: in the cases of sufficient air escape angles, air in the concrete will naturally run away and water/air passages will not form there; in the cases of insufficient air escape angles, from the apex of the steel tube water/air passages will take form between the concrete and the tube wall, then air in the concrete will be siphoned along those passages by the vacuum pump, consequently the distress of interfacial separation will be avoided.

3.2.3. Deficiency of the vacuum-aided grouted testing tube

Through comparison of the cutting inspection results between the 1# and 2# testing tubes, the vacuum-aided grouted 2# testing tube still has such a deficiency as the rather wide water/air passages. In the review of the construction process it was found that, near the completion of concrete grouting in the 2# tube, the connection pipe between the slurry pipe and the vacuum pump was opened to discharge the waste grout, or else the grout would be sucked into the vacuum pump to cause mechanical faults. Unfortunately, not a full-process vacuum-aided grouting operation was realized in the 2# tube, since the highest-point slurry pipe was opened to discharge grout, simultaneously let the outside air in and cancel the vacuum aid, just before the concrete arrived at the highest point to fill up the tube in a final step when the vacuum aid was exacted. Consequently, not only were the water/air passages formed before blocked off but also the front water/air passages in negative pressure sucked in the outside air, that caused abnormal interfacial concrete separation in the tube crown part with the vacuum-aided technique even severer than with the normal pressure procedure. As a countermeasure, a big slurry tub shall be set between the slurry pipe and the vacuum pump, to contain the released front grout or waste concrete and meanwhile keep the expected negative pressure state till perfect filling-up of concrete in the tube, thus a full-process vacuum-aided grouting operation will be realized.

4. VACUUM-AIDED GROUTING PRACTICE IN A REAL BRIDGE

4.1. The implementation scheme

According to the cubage of the tubes to be grouted, the concrete mixing throughput in situ and the transporting capacity of the concrete pump, a 3-level full-process vacuum-aided continuous pumping procedure was schemed, as was shown in Fig. 9, and the grouting order was shown in Fig. 10.

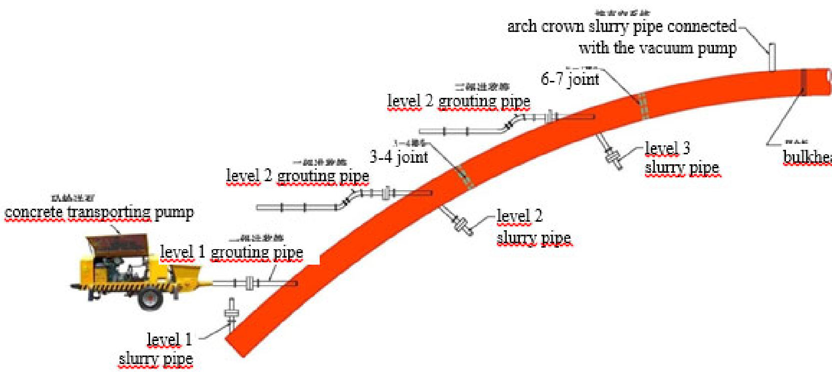


Fig. 9. *The setup for the 3-level full-process vacuum-aided continuous pumping procedure.*

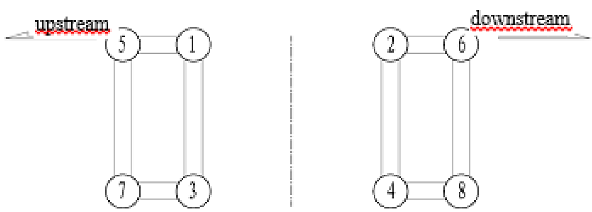


Fig. 10. *The order for concrete casting in the main chord tubes of the Hejiang Changjiang River 1st Bridge.*

4.1.1. *Vacuum* pumping

For example, the vaccum pumping operation at the 1# arch rib on the Chongqing bank involved an air volume of about 370 m^3 and took a time of 24'4", and obtatined a specified negative pressure of -0.08 MPa in the rib tube. With the advance of concrete casting in the tube, the vacuum degree would fall gradually. So the vacuum pump shall be started again as soon as the vacuum degree fell below -0.06 MPa, to replenish that degree back to -0.08 MPa.

4.1.2. Improvement of the testing vacuum-aided grouting technique

Since in the above tests not a full-process vacuum-aided grouting procedure was realized and excessively wide water/air passages occurred as a non-negligible deficiency, an improving countermeasure was proposed and implemented in the construction of the real bridge: a hollow steel tube with a volume of 4m^3 was used as a slurry tub placed on the crown of the arch rib, to connect the highest-point slurry pipe with the vacuum pump. The addition of this slurry tub allows for discharge of waste grout or concrete into the tub but avoids opening of the slurry pipe and letting outside air in, and effectively keeps the expected vacuum degree in the tube. Thus the realization of a full-process vacuum-aided grouting procedure was insured in the real bridge construction with a vacuum-pumping system shown in Fig. 11 (there the grey horizontal tube was the slurry tub).

The slurry tub came into use for the concrete casting in the 3rd main tube of the real bridge and its good effects were proved in practice, which maybe meant the first-time realized full-process vacuum-aided grouting procedure for concrete casting in arch rib steel tubes in the world.

Fig. 11. *The vacuum-pumping system on the arch crown of the real bridge.*

4.1.3. Vacuum-aided concrete casting practice

For the Hejiang Changjiang River 1st Bridge, it took 42d to complete all the concrete casting work in the 8 main chord tubes, each accomplished smoothly within a time from 13h to 19h.

4.2. Effects of vacuum-aided concrete casting in the real bridge

4.2.1. Judging criteria and cross sections chosen for inspection

Judging criteria:
According to the previous research work and the tube diameters of the real bridge, the judging criteria for the effects of vacuum-aided concrete casting were formulated and listed in Tab. 1.

Table 1. *The judging criteria for ultrasonic detection of concrete compactness in steel tubes of the Hejiang Changjiang River 1st Bridge.*

No.	wave velocity range	waveform quality	hammering sound quality	synthetic judgement
I	≥ 3600 m/s	clear and regular	dull	high concrete compactness, good interfacial bond
II	3300 ~ 3600 m/s	clear and regular	dull	high concrete compactness, goodish interfacial bond
III	≥ 3300 m/s	almost clear or with tiny waves	with slight echo	high concrete compactness, almost insufficient interfacial bond
IV	＜ 3300 m/s	almost clear or with tiny waves	with slight echo	substandard concrete compactness and insufficient interfacial bond

Cross sections chosen for inspection:

The positions of cross sections chosen for inspection and the detection channels on a cross section were shown in Fig. 12. Cross section 0 was at the skewback on the Chongqing bank (there's no internal flange but concrete in the tube at section 0, while there's internal flanges with concrete in the tube at other sections due to the need of segmental hoisting and joining), cross section 1 was between hoisting segments 1 and 2 on the Chongqing bank, cross section 9 was the closure section at the arch crown, and cross section 17 was between hoisting segments 1 and 2 on the Yibin bank. The arrangement of detection channels was similar to that in the tests: channel 1 in the vertical direction, 3 the horizontal, and 2, 4 the 45-inclined. For the 1# arch rib all the chosen cross sections were inspected, otherwise only sections 6-9 near the Chongqing bank plus section 3 or 1 were inspected.

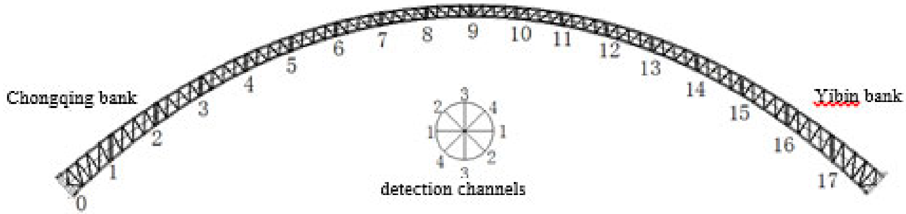


Fig. 12. *Numbers of the cross sections for ultrasonic detection and the detection channels on a section.*

4.2.2. The inspection results

Hammering inspection:

After the completion and initial setting of the concrete in the steel tubes, the hammering inspection was conducted, the results indicated that, all the concrete in the main chord tubes were cast with high compactness, and no cavity or interfacial separation was found around the internal flanges and arch crown parts where the concrete were hardly cast with high quality previously. The effects of the vacuum-aided grouting technique were much better than those of the traditional procedure.

Ultrasonic inspection:

For the 1# (numbered in the casting order) main chord tube the concrete was cast with the original vacuum-aided grouting technique, where no slurry tub was placed on the arch crown. At age 2d of the concrete in the tube, the wave velocities detected along the channels on most of the chosen cross sections were between 4500 m/s ~ 4800 m/s, meaning sound casting quality; but on the cross sections near the arch crown the vertical detection channels gave relatively low wave velocities and there interfacial separation was found during the hammering inspection, as were shown in Fig. 13a. After age 49d, the wave velocities detected along the channels on most of the chosen cross sections were between 3300 m/s ~ 4000 m/s, obviously lower than those at age 2d, for which and other situations in situ it was inferred that the steel tube-concrete bond failed to some extent. Afterwards, the detected wave velocities stopped falling down, indicating the above-said slight bond failing was not likely to develop into interfacial separation, as were shown in Fig. 13b.

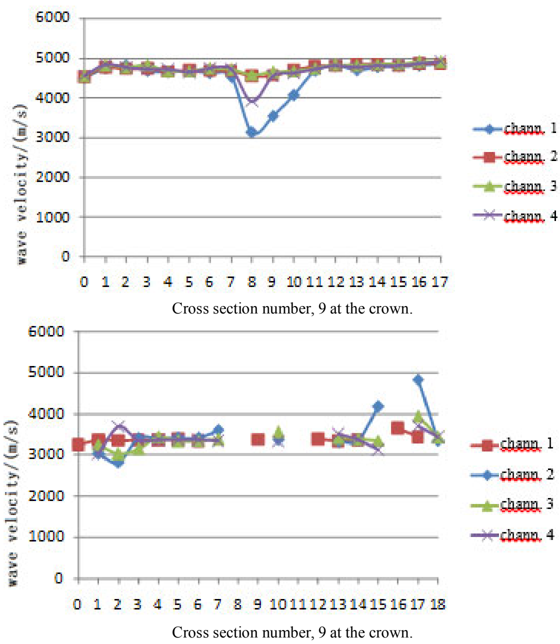
a)
b)


***Fig. 13**. Wave velocities detected at age: a) 2d; b) 49d of the concrete in the 1# main chord tube.*

Through addition of the slurry tub and realization of the full-process vacuum-aided grouting procedure, the concrete casting quality were greatly improved, for example, in the 6# main chord tube all the detected wave velocities at age 2d were beyond 3900 m/s and those at 25d beyond 3300 m/s, as were shown in Fig. 14a,b.

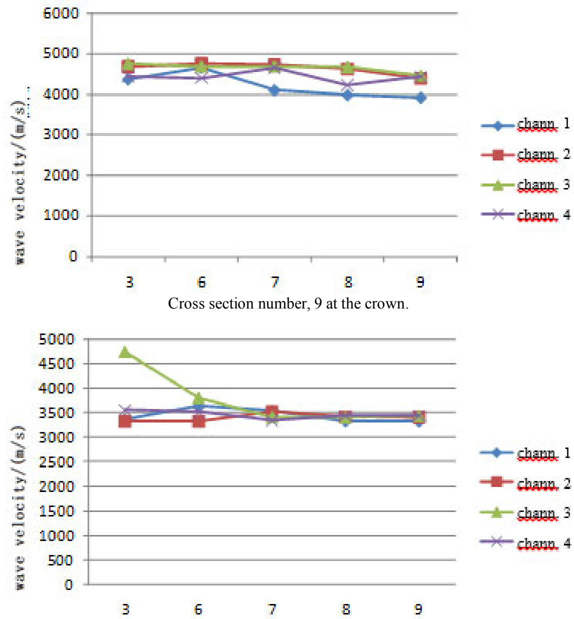


Fig. 14. *Wave velocities detected at age: a) 2d; b) 25d of the concrete in the 6# main chord tube.*

Drilling inspection

6 months after the concrete casting in the steel tubes, through drilling inspection on all the arch ribs it was found that the points of interfacial separation distances over 1mm were mostly located within the ±50m range around the arch crown, as were shown in Fig. 15.

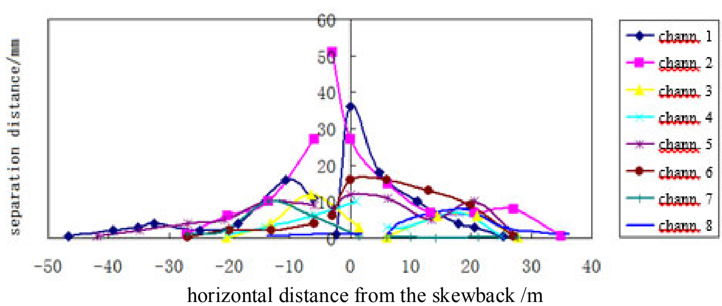


Fig. 15. *The results of drilling inspection on the 8 arch ribs.*

Evidently, the interfacial separation was severer in the 1# and 2# arch ribs with concrete cast earlier than in those with concrete cast later, where the largest interfacial separation distance was 51 mm in the 2# arch rib; after the improvement of the original vacuum-aided grouting technique, the full-process vacuum-aided grouting procedure was realized in the 3# rib (with altogether 6 steel tubes) where the long-time interfacial separation distances were below 15 mm, and in 4 tubes therein those were below 10 mm. These facts prove again the merits and necessity of the full-process vacuum-aided grouting procedure.

4.3. Economic aspects

The vacuum pumping equipment was recyclable, thus the equipment used for the construction of the Hejiang Changjiang River 1st Bridge was successively recycled in the construction of another 2 super-span arch bridges. This vacuum-aided grouting technique brought an amortized cost rise as low as only RMB14.2 per m^3 of concrete, gaining a substantial concrete quality promotion via a fairly small invest.

5. CONCLUSION

The proposed full-process vacuum-aided grouting technique, with only the addition of a small amount of recyclable vacuum pumping equipment and some simple steps to the traditional normal-pressure grouting procedure, could insure high compactness of the concrete cast in the steel tubes, avoid the interfacial concrete separation usually occuring around the skewbacks and other parts except the ±50 m ranges at the arch crowns, and greatly reduce the interfacial separation distances within the ±50 m ranges at the arch crowns (some materials revealed the interfacial separation distances measured in a super-span CFST bridge were between 0.5 mm and 30 mm, and were scattered from the skewback to the arch crown). This technique was successfully applied to the Hejiang Changjiang River 1st Bridge and patented thereafter, in turn it was generalized to the construction of the Nanpanjiang Bridge (a rigid frame RC arch bridge with a main span of 416 m) on the Yun-Gui High-Speed Railway, the Guangxi Guigang Yujiang Bridge (a CFST arch bridge with a main span of 270 m) and the Guangxi Qinzhou Qinjiang Bridge (a CFST arch bridge with a main span of 252 m) on the Liu-Qin Expressway, making great senses for the development of the CFST arch bridges.

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