

Experimental studies on void detection in concrete-filled steel tubes using ultrasound

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ABSTRACT

Due to shrinkage and/or inadequate compaction during concreting, voids may develop in a concrete-filled steel tube (CFST) between the concrete core and outer steel tube, which reduce the confinement effect of the steel tube on the concrete core, and further, decrease the load-carrying capacity and ductility of a CFST. In this study, an ultrasonic technique is utilized for quantifying voids in CFSTs by analyzing the ultrasound travel time in them. Four

24 potential travel paths are identified in CFSTs with/without pre-set voids. By making a
25 comparison of the experimental and theoretical ultrasound travel time, the actual ultrasound
26 travel path is determined in CFSTs. Further, by analyzing the matrix of ultrasound travel time
27 obtained from experiment, a novel method is proposed to generate the chromatogram of the
28 distribution of ultrasound travel time, which is utilized to quantify the voids in a CFST. The
29 chromatogram intuitively shows the position and geometry of the voids in CFSTs and is in
30 reasonable agreement with the pre-set voids. This study, therefore, establishes a new
31 method for quantifying voids in a CFST through the ultrasonic technique.

32 **Keywords:** Concrete-filled steel tube; void area; ultrasonic testing method; propagation path;
33 chromatogram; de-bonding

34

35 **1. Introduction**

36 In the pursuit of good structural performance, low costs and/or a large floor space in modern
37 structures, concrete-filled steel tubes (CFSTs) have been widely adopted as structural
38 elements, such as truss elements in arch bridges and columns in high-rise buildings. In a
39 CFST, the outer steel tube provides the lateral confinement to the concrete core so that the
40 concrete compressive strength can be significantly enhanced. Meanwhile, local buckling of
41 the steel tube can be restrained by filling it with concrete, resulting in a CFST's load carrying
42 capacity to be greater than the sum of the individual component load carrying capacities i.e.
43 steel tube and concrete core column [1]. To achieve the expected confinement effects with
44 loading being transferred between the two materials, it is necessary to ensure excellent
45 bonding between the concrete core and the steel tube. However, de-bonding between

46 concrete and steel is almost inevitable in a CFST, which can be classified into two categories,
47 i.e. shrinkage voids and near-wall cavity voids caused by deviation in deformation between
48 steel and concrete [2]. The defects in a CFST can reduce the confinement effect of the steel
49 tube on concrete, consequently decreasing its load-carrying capacity and ductility. Therefore,
50 it is significant to quantify the internal defects in a CFST to assess its structural performance
51 using the nondestructive testing (NDT) methods.

52 So far, several NDT methods have been developed for applications in civil engineering
53 community, such as ultrasonic testing [3], acoustic emission [2], infrared thermography [4]
54 and the impact-echo method [5]. Among them, the ultrasonic testing method has become
55 one of the most popular NDT techniques due to its versatility and convenient mode of
56 operation. It has been verified as a promising technique for the evaluation of crack
57 propagation in concrete [6, 7], delamination of concrete bridge decks [8], defects inside plain
58 and reinforced concrete [9], corrosion of steel reinforcement [10] and local yielding of steel
59 structures [11]. However, it is still very challenging to use the traditional ultrasonic testing
60 method to detect the de-bonding in composite elements in civil engineering structures, e.g.
61 fiber reinforced plastic (FRP) confined concrete and CFSTs. Although the ultrasonic
62 tomography can detect voids in concrete, the results are usually affected by the sizes and
63 shapes of coarse aggregates [12]. Particularly, it is difficult for ultrasonic waves to penetrate
64 deep into a highly attenuative material, e.g. epoxy resins used in the matrix of composite
65 materials. In response to this, Feng et al. [13] developed an electromagnetic imaging
66 technology to detect the de-bonding between FRP and concrete. However, the
67 electromagnetic ultrasonic waves failed to penetrate the steel tube. Therefore, it cannot be

68 used for assessing CFSTs. Meanwhile, some researchers tried to utilize ultrasound to
69 evaluate defects in CFSTs based on the difference in velocities travelled by ultrasound in
70 steel and concrete [14, 15], respectively. Their results showed that concrete quality in a
71 CFST can be qualitatively classified based approximately on the difference in ultrasonic
72 velocity picked up from experiment. However, it is almost impossible to determine the
73 positions and geometries of voids in CFSTs using their method. Therefore, when quantitative
74 detection of de-bonding (i.e. determination of both the positions and geometries of voids) in
75 CFSTs is a matter of concern, the extent of application and effectiveness of ultrasonic
76 technology remains as an under-researched topic. Recently, a piezoelectric (PZT) ceramic
77 transducer-based method [16] has been widely used in the detection of de-bonding in
78 composite reinforced concrete [17], steel reinforced concrete [18, 19] and CFSTs [20, 21].
79 However, it is necessary to embed these sensors into concrete during its casting, which
80 limits its applications on existing structures [22]. Therefore, the development and
81 implementation of NDT technology for convenient and direct detection of de-bonding in
82 CFSTs is still a challenge in civil engineering field.

83 In response to this problem, this paper aims at developing a de-bonding detection method
84 for CFSTs using the traditional ultrasonic technology. The previously mentioned ultrasound
85 methods identified the de-bonding based on the variations in ultrasound velocity, amplitude,
86 and frequency, however, the proposed method in this study will employ only the ultrasound
87 travel time to quantify the two types of de-bonding. By comparing the ultrasound travel time
88 obtained from experiment and theoretical analyses, the ultrasound travel paths in CFSTs
89 with the two categories of de-bonding voids can be obtained. Moreover, by analyzing the

90 ultrasound travel time obtained from experiment at a number of testing points in a CFST, a
91 matrix of ultrasound travel time can be derived. Further, the chromatogram of the distribution
92 of ultrasound travel time can be constructed, which can intuitively reflect the outline of voids,
93 consequently enabling quantitative evaluation of defects in a CFST. It is expected that the
94 method proposed in this study can provide new insight by using ultrasound travel time, as
95 the only required input data, for detecting the position and geometry of voids in a CFST. This
96 would characterize ultrasonic technology as a simple, convenient and effective technique
97 with an inherent low cost for detection of voids in CFSTs.

98

99 **2. Ultrasound travel path**

100 The two categories of de-bonding in CFSTs depend on the origins of formation [2]. One is
101 caused by concrete shrinkage, resulting in circumferential voids between the concrete core
102 and the outer steel tube. Its characteristic is that the thickness and length of the de-bonding
103 gap are small, but the scope along the circumference is large. The other category of
104 de-bonding is caused by the poor compaction during concrete casting, resulting in voids
105 forming near the inner wall of a steel tube. Its characteristic is that the length of the
106 de-bonding area along the axial direction of a CFST is large, but the scope along the
107 circumference is small. According to Fermat's principle, the ultrasonic wave would be
108 transmitted along the path of least travel time. Since the ultrasound velocity is 340 m/s in air
109 and 4000-6000 m/s in concrete, the ultrasonic wave may bypass the void area and transmit
110 along the path of least travel time. Therefore, the ultrasound travel time τ will increase if
111 there are defects existing in a CFST. Meanwhile, the path of the ultrasonic wave is complex

112 due to the effect of the steel tube wall. Therefore, the path should be determined in advance
113 to quantify voids in a CFST.

114 When the ultrasonic actuator and receiver are symmetrically positioned on the points A and
115 A' (see Fig.1) along the radian direction of the circular cross-section of a CFST, there are
116 four potential paths that the ultrasonic wave can transmit in a CFST: (1) penetrate the wall of
117 the steel tube and the concrete core of a CFST with no void, i.e. straight from Points A to A'
118 as shown in Figure. 1 (a); (2) bypass the void area and transmit along the wall of the steel
119 tube from Points A to B, then travel straightly through the concrete, i.e. from Points B to A' as
120 shown in Figure. 1 (b); (3) penetrate the void area and transmit straight through concrete, i.e.
121 from Points A to A' as shown in Figure. 1(c); and finally (4) transmit along the wall of the steel
122 tube only, i.e. from Points A to A' through Point B as shown in Figure. 1(d) without through
123 concrete.

124 In a well-compacted CFST, the ultrasonic wave will travel following Path 1 as shown in
125 Figure.1 (a). The corresponding ultrasound travel time τ_1 can be calculated using Eq. (1).

$$126 \quad \tau_1 = \frac{2t}{v_s} + \frac{D-2t}{v_c} \quad (1)$$

127 where, t is the thickness of the steel tube wall, D is the outer diameter of the steel tube, v_s is
128 the ultrasound velocity in steel, and v_c is the ultrasound velocity in concrete.

129 In a CFST with a void, the potential ultrasound travel paths are Paths 2, 3 and 4 as shown in
130 Fig. 1, and have the corresponding ultrasound travel time τ_2 , τ_3 and τ_4 which can be
131 calculated using Eqs. (2), (3) and (4), respectively, as following:

$$132 \quad \tau_2 = \frac{2t}{v_s} + \frac{L_{AB}}{v_s} + \frac{L_{BA'}}{v_c} \quad (2)$$

133
$$\tau_3 = \frac{2t}{v_s} + \frac{d}{v_a} + \frac{D-2t-d}{v_c} \quad (3)$$

134
$$\tau_4 = \frac{2t + 0.5 \cdot \pi (D - 2t)}{v_s} \quad (4)$$

135 where, L_{AB} is the arc length between points A and B in Fig. 1 (b); $L_{BA'}$ is the distance
 136 between points B and A'; v_a is the ultrasound velocity in air; and d is the thickness of the
 137 void area along the travel path. Such a method will ensure that the actual travel path is
 138 determined by comparing the travel times of the three potential travel paths. The travel path
 139 with the shortest travel time will be the actual travel path of the ultrasonic wave.

140

141 **3. Experimental program**

142 **3.1 Preparation of CFST specimens**

143 There are 6 CFST circular columns tested in this study, with an outer diameter of 219 mm, a
 144 height of 500 mm, and a steel tube wall thicknesses of 5.3 mm. The CFST is made of grade
 145 Q235 steel, and grade C50 concrete. The 6 specimens were divided into two groups. 3
 146 specimens, denoted as NT-1, NT-2 and NT-3, were used to demonstrate the detection of the
 147 first-category voids, i.e. defects caused by concrete shrinkage while the other 3 specimens,
 148 denoted as NT-4, NT-5 and NT-6, were used to demonstrate the detection of the
 149 second-category voids, i.e. defects caused by poor compaction in construction. Taking the
 150 specimens NT-2 and NT-5 as an example, Fig. 2 shows the two categories of voids in
 151 CFSTs.

152 In the case of the first-category void, the thicknesses of spacer d were 3.0, 4.5 and 7.0 mm
 153 for specimens NT-1, -2, and -3, respectively. The geometries and position of the spacer are

154 sketched in Fig. 3. Before casting concrete, the spacers were closely attached on the inner
155 surface of the wall of the steel tube. They were removed right after the initial setting of
156 concrete. By such measures, pre-set voids with various thicknesses and arc lengths were
157 obtained, which were distributed along the axial direction of the CFST specimens in a
158 ladder-like manner. The cross-sections of the first-category void at the heights of 150 to 250
159 mm, 250 to 350 mm and 350 to 400 mm are shown in Fig. 4 (a), (b) and (c), respectively. It
160 can be seen that void area increases with height.

161 In the case of the second-category void, the thicknesses of spacer d were 10, 30 and 50 mm
162 for specimens NT-4, -5, and -6, respectively. The geometries and position of the spacer are
163 illustrated in Fig. 5. It should be noted that the elevations of the spacer with the chord length
164 of 92, 162 and 213 mm shown in Fig. 5 correspond to specimen NT-4, -5, and -6,
165 respectively. The cross sections of specimen NT-4, -5, and -6 with the pre-set second
166 category void are shown in Fig. 6 (a), (b) and (c), respectively.

167

168 **3.2 Distribution of testing points**

169 The ultrasonic generator used for this study was a TICO-series ultrasonic generator
170 produced by Proceq in Switzerland. The ultrasound used for this study had a frequency of 54
171 kHz. Each CFST column was divided into 10 segments of equal length along its axial
172 direction. The testing sections were set from 100 to 450 mm, with 50 mm interval, above the
173 column footing, denoted as Sections A to H. At each section, 12 testing couples were set at
174 15° interval along its outer circumference. In total 12 pairs of the ultrasonic actuators and
175 receivers were symmetrically mounted on the outer surface of the steel tube of each CFST

176 column along its circumferential direction, such as 1-1', 2-2' etc. as illustrated in Figs. 4 and
177 6. Therefore, in total 96 testing points were set for each CFST specimen as shown in Fig. 7.

178

179 **4. Results and discussions**

180 ***4.1 Ultrasound travel in compact CFSTs***

181 To get a stable ultrasound travel time, all tests were carried out at the concrete age of 60
182 days. Meanwhile, 100-mm concrete cubes were cast in parallel with the CFST specimens to
183 test the ultrasound velocity in concrete also at the age of 60 days. The steel tubes prepared
184 for the experiment were used to test the ultrasound velocity in steel before filling with
185 concrete. The average ultrasound velocities measured in concrete and steel were 4880 and
186 5620 m/s, respectively, in this study. To measure the ultrasound travel time in a CFST with
187 well-compacted concrete, one testing section from each of the NT-3, -4, -5 and -6 specimens
188 was selected. These testing sections are denoted as NT-3-B, NT-4-A, NT-5-F and NT6-C,
189 respectively. For instance, NT-4-A denotes section A, with the height of 50 mm above the
190 footing, of specimen NT-4. The measured ultrasound travel times corresponding to the 12
191 couples of testing points at each section are listed in Table 1. According to Eq. (1), the
192 theoretical value of τ_1 should be 44.6 μs in this study, which is in agreement with the
193 experimental results, which ranged between 43.7 and 48.6 μs , as shown in Table 1.
194 Therefore, it can be assured that the ultrasound travel path in the well-compacted area of the
195 CFST specimens is Path 1 as illustrated in Fig. 1 (a).

196

197 ***4.2 Ultrasound travel in CFST specimens with the first-category voids***

198 With respect to the first-category voids in CFSTs, experimental results of specimen NT-1 and
199 NT-3 are listed in Table 2, in which six testing sections, i.e., sections C to H of each
200 specimen were investigated to measure the ultrasound travel time. It can be seen from
201 experimental results that there are some significantly larger values of travel time measured
202 in certain testing points compared with neighbouring testing points, which are highlighted in
203 italic and underlined in Table 2. The range of the highlighted data is approximately
204 ladder-like, which has reasonable agreement with the pre-set void distribution in the
205 corresponding CFST specimen, suggesting the results are reliable.

206 If the ultrasound travels along Path 4, its travel time should be determined by the
207 semi-perimeter of the CFST specimen. Then, the travel time measured by each couple of
208 testing points along the circumference of a CFST specimen should be the same, which is
209 $61.2 \mu\text{s}$ according to Eq. (4). Similarly, if the ultrasonic wave travels along Path 3, its travel
210 time should be related to the thickness of the void when the void exists between a couple of
211 testing points. Then, the travel time measured by each couple of testing points should be
212 52.8 and $63.7 \mu\text{s}$, according to Eqs. (3), with respect to specimens NT-1 and NT-3,
213 respectively. However, by comparing with the experimental results in Table 2, the theoretical
214 travel time along Paths 3 and 4 shows distinct differences. Therefore, it can be confirmed
215 that the ultrasonic waves are not transmitted along Path 3 or 4 for the first-category void in a
216 CFST. If the ultrasonic waves transmit along Path 2, the theoretical travel time can be
217 calculated using Eq. (2), which is listed in Table 3. It should be noted that according to Eq.
218 (2), the void has no effect on the calculated results as the ultrasound bypasses the void,
219 therefore, the theoretical travel time should be the same for specimens NT-1, -2 and -3.

220 Comparing the highlighted data in Tables 2 and 3, it can be seen that both the distribution
221 and values of the highlighted data in the two tables are in reasonable agreement with each
222 other, indicating that the ultrasound should transmit along Path 2 in a CFST with the
223 first-category voids.

224

225 ***4.3 Ultrasound travel in CFSTs with the second-category voids***

226 The same analysis method is adopted for the investigation of ultrasound transmission in
227 CFST specimens with the second-category voids. In this case, two testing sections, H and G,
228 were investigated for each specimen and the measured ultrasound travel time in specimen
229 NT-4, -5 and -6 are listed in Table 4. It can be seen that the distribution of enlarged values of
230 travel time, as highlighted in italic and underscored in this table, reflects the positions of
231 voids in the three specimens (see Fig. 6). If the ultrasonic wave travels along Paths 4, a
232 uniform travel time, i.e. $61.2 \mu\text{s}$, should be obtained from experiment as per Eq. (4).
233 Meanwhile, if the ultrasound travels along Path 3, the theoretical maximum travel time in
234 specimen NT-4, -5 and -6 should be $72.0 \mu\text{s}$, $126.7 \mu\text{s}$ and $181.4 \mu\text{s}$, respectively, based on
235 Eq. (3). Therefore, it can be confirmed that the ultrasound did not travel along Path 3 or 4 in
236 specimens with the second-category voids because these data are obviously different from
237 the experimental ones listed in Table. 4. If the ultrasound travels along Path 2, the theoretical
238 travel time can be calculated using Eq. (2), which are listed in Table 5. Compared with the
239 highlighted data in Table 4, it can be seen that both the distribution and values of the
240 highlighted data in the two tables have a reasonable agreement, which indicates that the
241 ultrasound does travel along Path 2 in the CFST specimens with the second-category voids.

242 It should be noted that, in general, the ultrasound travel time obtained from experiment is a
243 bit greater than the corresponding theoretical ones for CFST specimens for both categories
244 of voids. Particularly, the experimental data becomes increasingly larger when the testing
245 points are close to the edge of void areas, such as the testing points NT-5-H-9 and NT-1-D-8.
246 By examining these areas, it can be found that, usually, there exists an imperfect contact
247 between the steel tube and concrete, e.g. loose and porous concrete filled inside. However,
248 the increment in the ultrasound travel time does not affect the identification of the voids. On
249 the contrary, it makes the qualitative detection of void edges in a CFST much easier.

250

251 **5. Chromatogram of ultrasound travel time distribution**

252 Although the void areas can be approximately detected based on the analysis of ultrasound
253 travel time listed in Tables 2 and 4, improvement is needed for quantifying voids, for example,
254 the judgment on the void edges is inaccurate and not intuitive. It is inconvenient to
255 compare the data one by one, which may result in the omission and mistake of the
256 determination of the voids. Therefore, the following research aims at imaging the voids in the
257 CFSTs based on the ultrasound travel time obtained in experiment. In summary, the
258 following steps are included in developing the images of voids in CFSTs:

- 259 1. Generate grids based on the testing points, which are the nodes of the grids
260 generated. Taking specimen NT-1 as an example, there is ultrasound travel time
261 from 8×12 testing points so that the half-cylinder can be on average divided into 8
262 $\times 12$ grids, in which 8 grids along the axial direction and 12 grids along the
263 circumferential direction.

- 264 2. Form the matrix of ultrasound travel time. By assigning the ultrasound travel time to
265 the corresponding nodes, the matrix can be obtained, in which the elements are the
266 ultrasound travel time.
- 267 3. Densify the grids. To get a more accurate void area in the derived images, the grids
268 should be re-fined so that the smooth edge of the void can be obtained. In this study,
269 each grid derived from the previous step is divided into 50×50 grid nodes, making
270 the half-cylinder be divided into 400×600 grid nodes.
- 271 4. Form the densified matrix of ultrasound travel time. Through introducing the V4
272 interpolation method provided by MATLAB software, the ultrasound travel time at
273 each of the 400×600 grid nodes can be obtained.
- 274 5. Draw the chromatogram of the distribution of ultrasound travel time using MATLAB
275 based on the densified matrix obtained in step 4.

276 Using the abovementioned steps of analysis, the chromatogram of the CFST specimens
277 tested in this study can be derived, and are illustrated in Fig. 8. In the case of the
278 first-category voids, i.e., in specimens NT-1, -2 and -3, it can be clearly seen that the void
279 heights are 200–450 mm from the footing of specimens, and are in approximately a
280 ladder-like distribution along the axial direction (see Fig. 8 (a), (b) and (c)). Meanwhile, in the
281 case of the second-category voids, i.e., in specimens NT-4, -5 and -6, the figures explicitly
282 illustrate the geometries of the voids, which have a height of 350-450 mm from the footing of
283 specimens and circumferential angles from $45-75^\circ$, $60-120^\circ$ and $105-195^\circ$, respectively
284 (see Fig. 8 (d), (e) and (f)). It should be noted that there are some areas highlighted in red in
285 the chromatogram, which are not pre-set voids in the experiment, such as the area with

286 height of 100-250 mm and circumferential angle of 30° -90° shown in Fig. 8(d). Through an
287 examination of this area after testing, it was found that some of the concrete filled inside was
288 loose and porous, increasing the ultrasound travel time. Therefore, by comparing with the
289 pre-set voids in CFST specimens as shown in Figs. 4 and 6, the derived chromatogram
290 shows a reasonable agreement with respect to the positions and geometries of the voids.

291 To study the effects of concrete age using the chromatogram, similar tests were conducted
292 on the CFST specimens at the ages of 7, 28 and 90 days with the results presented in Fig. 9.
293 Although the color is slightly different in the chromatograms, the geometries of the detected
294 voids are almost the same, suggesting that concrete age has little effects on the
295 determination of voids, so that the chromatogram method proposed in this study can be
296 employed for detecting the voids in CFSTs both under construction and in service.

297 In practical engineering, detecting the voids more effectively and at the lowest possible cost
298 is of prime importance. Therefore, it is necessary to study the effects of the number of
299 testing points on the accuracy of detection of the voids. Taking specimen NT-3 as an
300 example, 4, 6 and 12 couples were utilized to test the ultrasound travel time, and then form
301 the corresponding chromatograms, which are shown in Fig. 10(a), (b) and (c), respectively.
302 When 4 couples of testing points are adopted, the obtained chromatogram of the void area is
303 blurred and spread (see Fig. 10 (a)). The height of the void can be determined roughly, but
304 the range along the circumference demonstrates large deviation, in which only one
305 ladder-like distribution pattern can be found. With the increase of testing points from 4 to 6
306 couples, the derived chromatogram can approximately reflect the pre-set voids in the
307 specimens (see Fig. 10 (b)). When the testing points increase to 12 couples, the derived

308 chromatogram has a better agreement with the experimental results (see Fig. 10 (c)).
309 However, compared with Fig 10 (b), the improvement in Fig 10 (c) is not significant.
310 Therefore, it is concluded that 6 couples of testing points can appropriately meet the
311 requirement of void detection in practical engineering.

312 It is worth pointing out that the symmetrical ultrasonic testing and the imaging methods can
313 be used only in the case that the ultrasonic wave travels along Path 2 shown in Fig. 1, i.e.,
314 $\tau_1 < \tau_2 < \tau_4$. The minimum central angles corresponding to the voids can be determined
315 according the criteria of $\tau_1 < \tau_2$, and the maximum one can be determined according to the
316 criteria $\tau_2 < \tau_4$. Through substituting Eqs (1), (2) and (4) into the equations, the scopes of the
317 central angles corresponding to the voids are listed in Table 6. It should be noted that the
318 minimum central angles are less influenced by the ultrasonic wave velocities in different
319 concrete, so the values can be approximately determined as 12° . The scenario is different in
320 the case of the determination of maximum central angles. Since the ultrasonic wave
321 velocities in different concrete vary from 4000 to 5400 m/s, the corresponding maximum
322 central angle ranges from 22 to 172° (see Table 6). Therefore, the minimum/maximum sizes
323 of voids that can be detectable depend on the diameter of CFST cross-section. In case of
324 smaller CFST, the minimum /maximum sizes of voids that can be detected are smaller. In
325 contrast, the sizes are greater for a bigger diameter CFST. Taking the CFST used in this
326 study as an example, the minimum size of void that can be detected is 20.7 mm.
327 Considering that the concrete strength grade for CFSTs should be greater than C50 for the
328 purpose of maximizing their advantages in structures, the corresponding maximum central
329 angle can be greater than 110° . Therefore, the symmetrical ultrasonic testing and imaging

330 methods are effective and suitable for the detection of de-bonding voids in the CFST
331 members.

332 Moreover, the scope of the void is determined by the actual ultrasound travel path, therefore,
333 the shape of the void will affect the measurement in certain case. For example in Fig 1(b),
334 the ultrasound travel between Points B and A' of concrete is not along a line, i.e. the void
335 enters the area surrounded by Line BA' and Arc BA'. In this case, the derived ultrasound
336 travel time will get longer so that the predicted void area will be larger than the actual one,
337 resulting in an over-estimation on the void size.

338

339 **6. Conclusions**

340 In this study, the symmetrical ultrasonic testing method was introduced to detect the
341 de-bonding voids in CFSTs. By investigating the variation of ultrasound travel time in the
342 CFST specimens with different categories of pre-set voids, the ultrasound travel path was
343 determined. Based on the experimental results from various testing points, the matrix of
344 ultrasound travel time can be obtained, in which elements of rows and columns represent
345 the results in the circumferential and the axial direction, respectively. To get a more accurate
346 image of voids in the CFST members, a densified matrix can be derived by interpolation of
347 the original matrix of ultrasound travel time. Finally, the chromatogram of the distribution of
348 ultrasonic wave travel time based on the derived densified matrix can be drawn using
349 MATLAB. The effects of concrete age and quantity of testing points on the chromatogram
350 were analyzed, and the scope of the symmetrical ultrasonic testing and imaging methods in
351 the detection of de-bonding voids in CFST members was discussed. Based on experimental

352 and theoretical studies, the following conclusions can be drawn:

353 (1) For the CFST members without a void, the ultrasonic waves penetrate the steel tube wall
354 and concrete and are transmitted in a straight line. In the case of CFST members with a
355 de-bonding void, the ultrasonic waves bypass the void area along the wall of the steel
356 tube and then travel through the concrete along a straight line.

357 (2) Based on the matrix of ultrasonic wave travel time obtained in experiment, the
358 chromatogram is derived, which can effectively and intuitively reflect the location and
359 geometry of de-bonding void areas in CFST members.

360 (3) Concrete ages have little effect on the determination of voids in CFSTs using the
361 chromatogram so that the method proposed in this study can be used to evaluate the
362 de-bonding in the CFST members under construction and in service.

363 (4) To reflect the position and geometry of the void area, at least 6 couples of testing points
364 must be arranged equally along the circumferential direction in a testing section. When
365 the number of testing points decreases to 4 couples, the obtained chromatogram may be
366 distorted resulting in an incorrect judgment on the void geometry.

367

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373

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441 **Captions of figures**

442 **Fig. 1.** Four potential paths of ultrasound transmission: (a); (b); (c); and (d)

443 **Fig. 2.** Two categories of pre-set voids in CFST specimens: (a) First-category void;
444 (b) Second-category void

445 **Fig. 3.** Spacer geometry and void position in CFST specimens with the pre-set first-category
446 void

447 **Fig. 4.** Cross sections of a CFST specimen at various heights with the pre-set first-category
448 void: (a) Height of 150-250 mm; (b) Height of 250-350 mm; and (c) Height of 350-400 mm

449 **Fig. 5.** Spacer geometry and void position in specimens with the pre-set second-category
450 void

451 **Fig. 6.** Cross sections of CFST specimens with the pre-set second-category void with
452 different void thickness: (a) $d=10$ mm; (b) $d=30$ mm; and (c) $d=50$ mm

453 **Fig. 7.** Distribution of testing points along axial and circumferential directions of a CFST
454 specimen (unit: mm)

455 **Fig.8.** Chromatogram of the distribution of ultrasound travel time: (a) NT-1; (b) NT-2; (c)
456 NT-3; (d) NT-4; (e) NT-5; and (f) NT-6

457 **Fig. 9.** Chromatograms of specimen NT-3 at various concrete ages: (a) 7 days; (b) 28 days;
458 and (c) 90 days

459 **Fig. 10.** Chromatograms of specimen NT-3 with different numbers of testing couples: (a) 4
460 couples; (b) 6 couples; and (c) 12 couples

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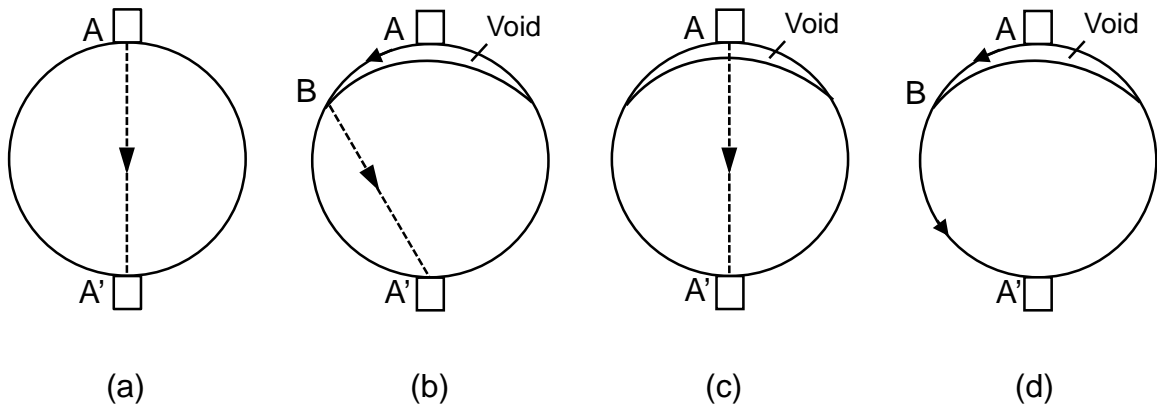


Fig. 1. Four potential paths of ultrasound transmission

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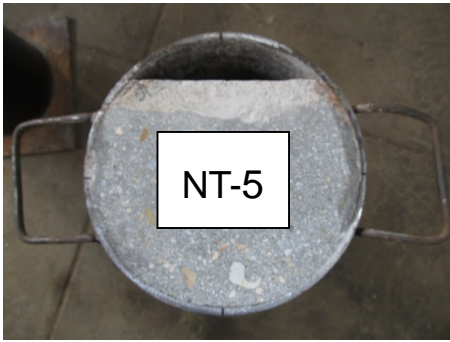
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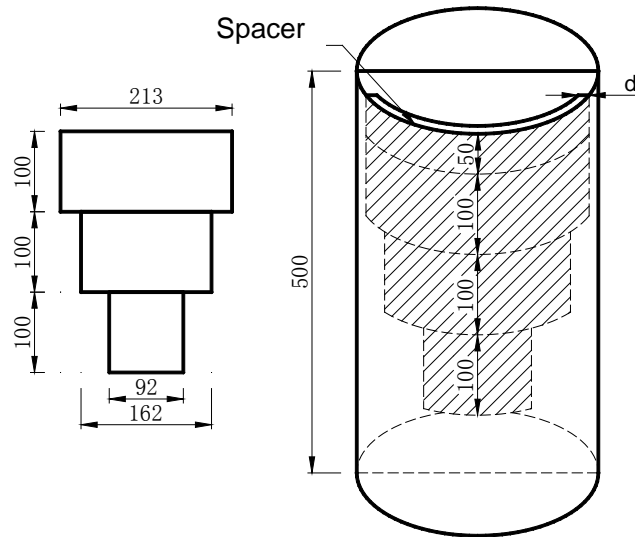
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(a) First-category void

(b) Second-category void

Fig. 2. Two categories of pre-set voids in CFST specimens



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505 **Fig. 3.** Spacer geometry and void position in CFST specimens with the pre-set first-category

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void

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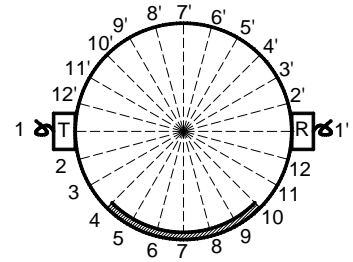
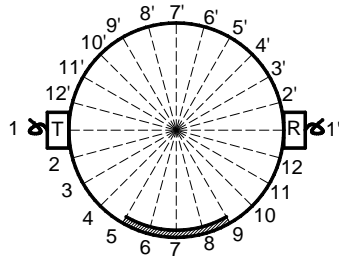
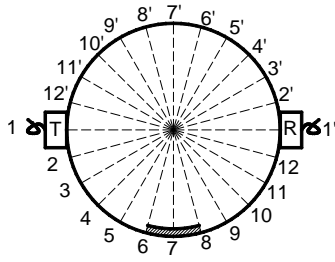
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521 (a) Height of 150-250 mm

(b) Height of 250-350 mm

(c) Height of 350-400 mm

522 **Fig. 4.** Cross sections of a CFST specimen at various heights with the pre-set first-category
 523 void

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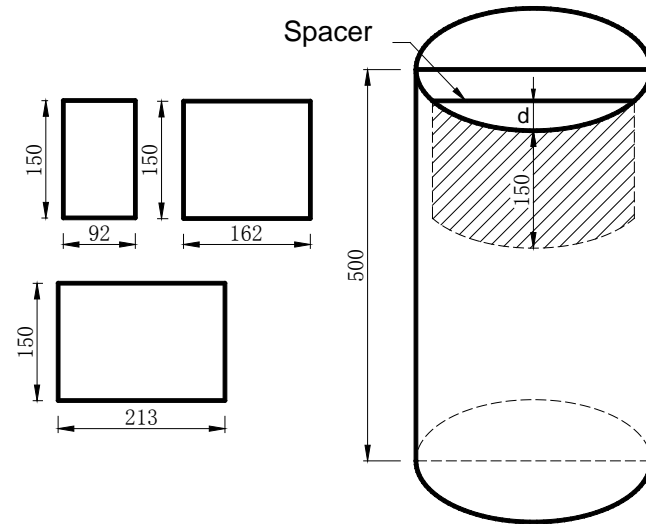
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541 **Fig. 5.** Spacer geometry and void position in specimens with the pre-set second-category

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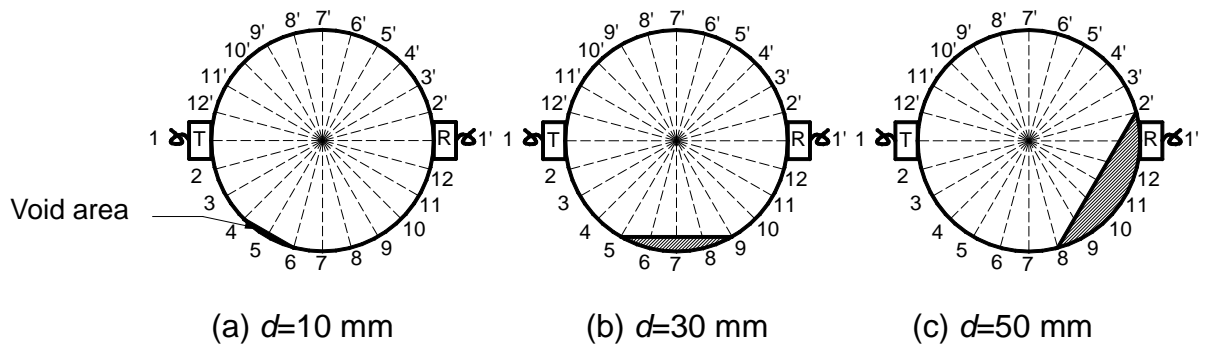
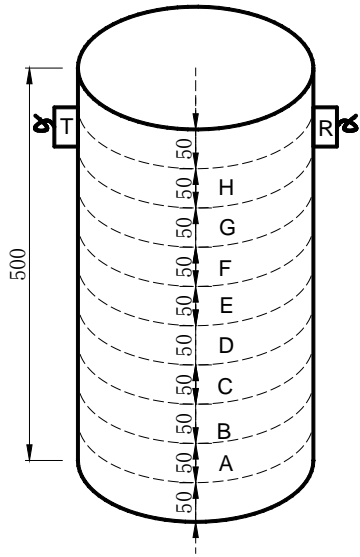
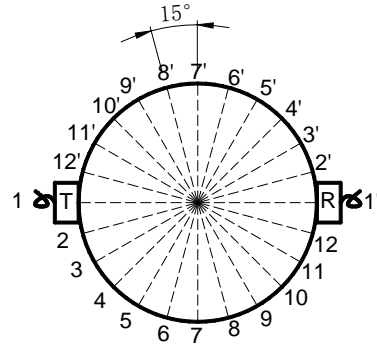


Fig. 6. Cross sections of CFST specimens with the pre-set second-category void with different void thickness



(a) axial



(b) circumferential

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579 **Fig. 7.** Distribution of testing points along axial and circumferential directions of a CFST

580 specimen (unit: mm)

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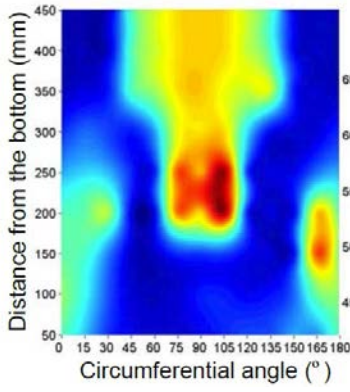
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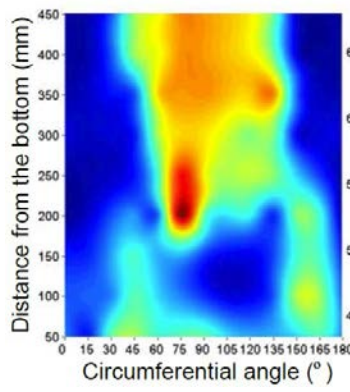
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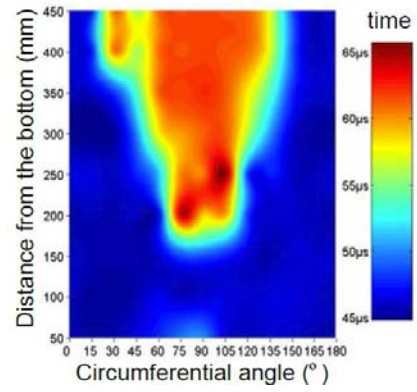
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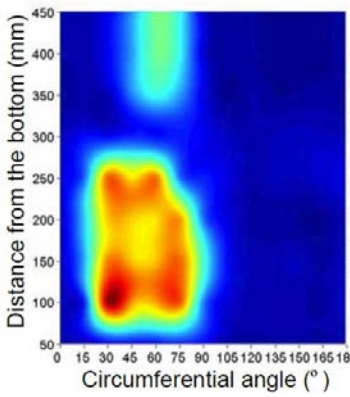
(a) NT-1



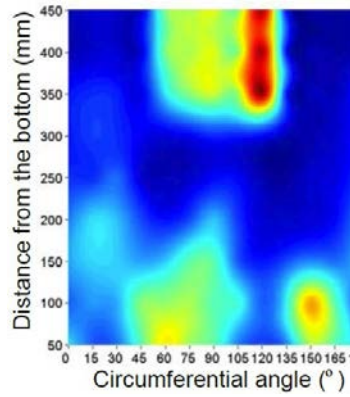
(b) NT-2



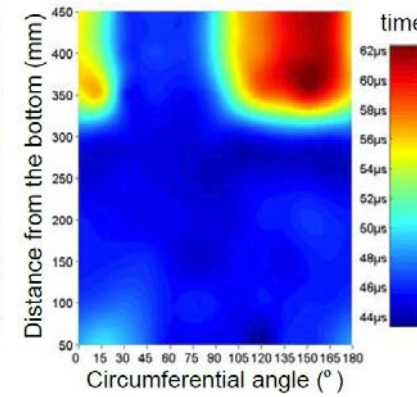
(c) NT-3



(d) NT-4



(e) NT-5



(f) NT-6

Fig.8. Chromatogram of the distribution of ultrasound travel time

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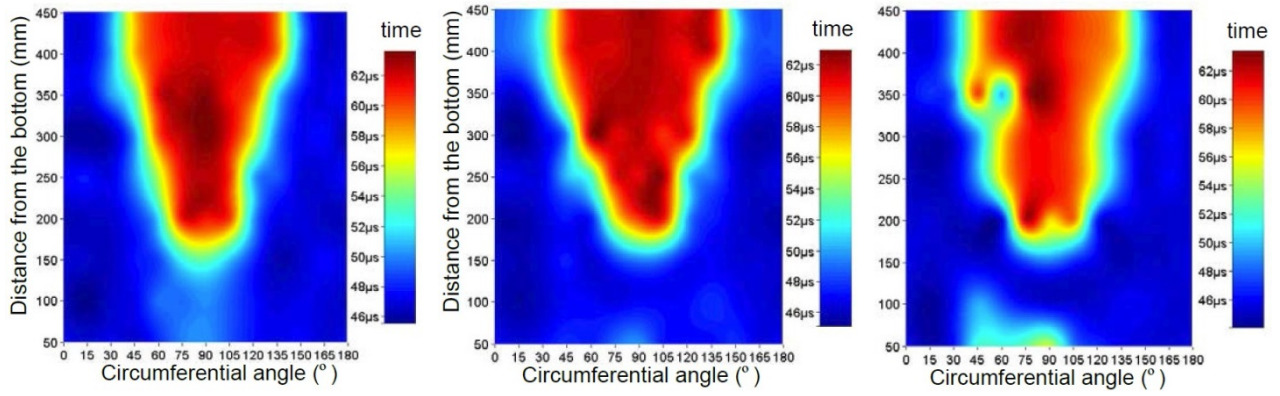
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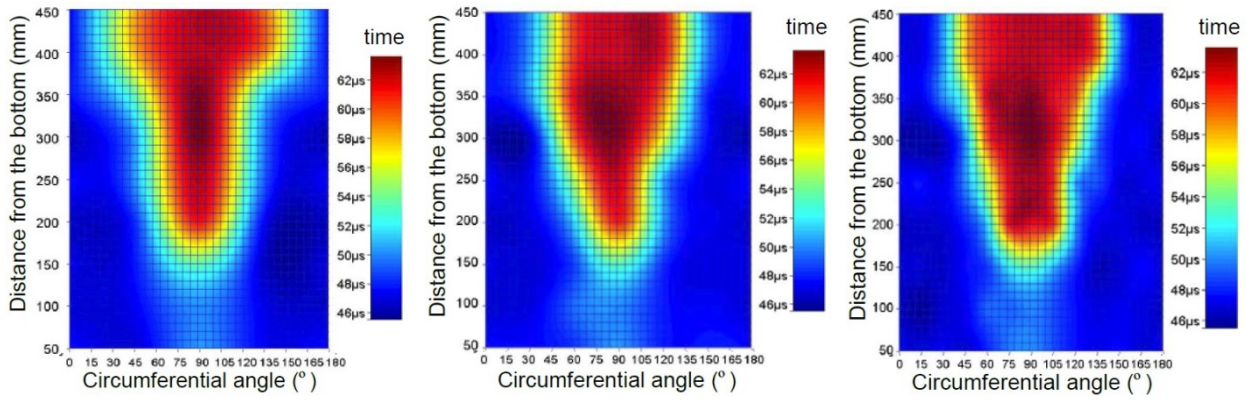


(a) 7 days

(b) 28 days

(c) 90 days

Fig. 9. Chromatograms of specimen NT-3 at various concrete ages



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(a) 4 couples

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(b) 6 couples

(c) 12 couples

629 **Fig. 10.** Chromatograms of specimen NT-3 with different numbers of testing couples

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646 **Table 1.** Ultrasound travel time (unit: μs) in well-compacted CFST specimens measured from
 647 experiment

Testing points	1	2	3	4	5	6	7	8	9	10	11	12
NT-3-B	45.7	45.1	45.1	45.5	46.8	45.8	46.2	46.5	46.1	46.4	46.4	46.0
NT-4-A	46.2	46.4	47.6	47.6	47.8	48.6	47.7	46.1	45.9	46.1	46.1	46.0
NT-5-F	47.2	48.2	47.7	46.5	46.1	46.6	47.8	47.4	46.9	45.0	44.9	45.5
NT-6-C	45.7	45.8	46.0	46.1	45.2	44.6	44.8	45.4	45.4	45.0	45.6	45.9

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650 **Table 2.** Ultrasound travel time (unit: μs) in the specimens of NT-1 and -3 measured from
 651 experiment

Testing points	1	2	3	4	5	6	7	8	9	10	11	12
NT-1-C	54.8	53.9	49.6	45.1	45.1	47.5	47.8	48.0	46.0	45.4	46.2	63.7
NT-1-D	54.3	54.6	56.9	45.5	46.0	<u>62.8</u>	<u>60.0</u>	<u>67.9</u>	46.8	45.8	45.8	60.2
NT-1-E	50.5	51.6	50.8	47.1	46.9	<u>63.4</u>	<u>60.8</u>	<u>67.8</u>	47.6	45.8	45.8	49.0
NT-1-F	47.2	48.9	47.9	46.8	<u>50.5</u>	<u>58.6</u>	<u>59.5</u>	<u>59.8</u>	<u>52.0</u>	46.3	45.4	45.4
NT-1-G	44.6	45.6	46.6	<u>54.1</u>	<u>56.5</u>	<u>59.7</u>	<u>60.3</u>	<u>58.6</u>	<u>57.6</u>	<u>57.8</u>	46.7	45.1
NT-1-H	44.3	44.7	45.0	<u>54.3</u>	<u>57.5</u>	<u>59.7</u>	<u>60.0</u>	<u>59.8</u>	<u>57.4</u>	<u>54.1</u>	45.9	45.1
NT-3-C	46.0	45.5	45.4	45.5	46.1	48.6	48.7	47.7	46.2	45.5	46.2	46.0
NT-3-D	45.2	45.8	45.3	46.0	46.8	<u>64.4</u>	<u>58.8</u>	<u>59.7</u>	48.2	46.3	46.1	45.8
NT-3-E	46.3	46.6	45.8	47.8	<u>51.3</u>	<u>60.3</u>	<u>60.4</u>	<u>65.5</u>	48.2	47.7	45.9	45.7
NT-3-F	44.8	44.8	45.2	<u>50.0</u>	<u>58.1</u>	<u>59.8</u>	<u>61.1</u>	<u>61.3</u>	<u>56.2</u>	<u>50.4</u>	46.1	45.3
NT-3-G	45.9	46.0	48.4	<u>53.4</u>	<u>61.1</u>	<u>61.6</u>	<u>62.3</u>	<u>61.3</u>	<u>58.0</u>	<u>53.8</u>	47.8	46.2
NT-3-H	46.4	47.7	<u>60.5</u>	<u>55.8</u>	<u>60.9</u>	<u>61.4</u>	<u>61.8</u>	<u>61.3</u>	<u>60.8</u>	<u>57.2</u>	48.9	45.7

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653 **Table. 3** Theoretical ultrasound travel time (unit: μs) along Path 2 in the first-category void

Testing points	1	2	3	4	5	6	7	8	9	10	11	12
C	44.6	44.6	44.6	44.6	44.6	<u>47.8</u>	<u>51.7</u>	<u>47.8</u>	44.6	44.6	44.6	44.6
D	44.6	44.6	44.6	44.6	44.6	<u>47.8</u>	<u>51.7</u>	<u>47.8</u>	44.6	44.6	44.6	44.6
E	44.6	44.6	44.6	44.6	<u>49.0</u>	<u>52.8</u>	<u>55.8</u>	<u>52.8</u>	<u>49.0</u>	44.6	44.6	44.6
F	44.6	44.6	44.6	44.6	<u>49.0</u>	<u>52.8</u>	<u>55.8</u>	<u>52.8</u>	<u>49.0</u>	44.6	44.6	44.6
G	44.6	44.6	44.6	<u>48.7</u>	<u>52.5</u>	<u>55.7</u>	<u>58.1</u>	<u>55.7</u>	<u>52.5</u>	<u>48.7</u>	44.6	44.6
H	44.6	44.6	44.6	<u>48.7</u>	<u>52.5</u>	<u>55.7</u>	<u>58.1</u>	<u>55.7</u>	<u>52.5</u>	<u>48.7</u>	44.6	44.6

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656 **Table. 4** Ultrasound travel time (unit: μs) in the specimens of NT-4, -5 and -6

Testing points	1	2	3	4	5	6	7	8	9	10	11	12
NT-4-H	46.0	46.3	46.7	<u>50.9</u>	<u>53.8</u>	<u>51.5</u>	47.5	45.7	46.3	45.9	46.0	46.1
NT-4-G	46.3	46.4	47.9	<u>51.4</u>	<u>55.6</u>	<u>53.6</u>	47.0	46.2	46.1	45.6	45.8	45.7
NT-5-H	47.0	47.7	47.4	46.1	<u>52.8</u>	<u>56.5</u>	<u>58.3</u>	<u>57.0</u>	<u>68.9</u>	47.2	45.2	45.0
NT-5-G	44.9	45.6	45.8	45.8	<u>56.2</u>	<u>57.3</u>	<u>58.7</u>	<u>56.5</u>	<u>67.9</u>	46.7	44.9	44.5
NT-6-H	<u>54.8</u>	<u>56.0</u>	46.0	45.9	45.6	45.5	<u>48.0</u>	<u>53.7</u>	<u>57.8</u>	<u>58.7</u>	<u>61.2</u>	<u>58.9</u>
NT-6-G	<u>55.0</u>	<u>52.3</u>	46.6	46.5	46.4	46.7	<u>50.8</u>	<u>55.9</u>	<u>57.6</u>	<u>60.1</u>	<u>61.0</u>	<u>60.9</u>

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659 **Table. 5** Theoretical ultrasound travel time (unit: μs) along Path 2 in CFSTs with the
 660 second-category void

Testing points	1	2	3	4	5	6	7	8	9	10	11	12
NT-4-H	44.6	44.6	44.6	<u>47.8</u>	<u>51.7</u>	<u>47.8</u>	44.6	44.6	44.6	44.6	44.6	44.6
NT-4-G	44.6	44.6	44.6	<u>47.8</u>	<u>51.7</u>	<u>47.8</u>	44.6	44.6	44.6	44.6	44.6	44.6
NT-5-H	44.6	44.6	44.6	44.6	<u>49.0</u>	<u>52.8</u>	<u>55.8</u>	<u>52.8</u>	<u>49.0</u>	44.6	44.6	44.6
NT-5-G	44.6	44.6	44.6	44.6	<u>49.0</u>	<u>52.8</u>	<u>55.8</u>	<u>52.8</u>	<u>49.0</u>	44.6	44.6	44.6
NT-6-H	<u>52.5</u>	<u>48.7</u>	44.6	44.6	44.6	44.6	44.6	<u>48.7</u>	<u>52.5</u>	<u>55.7</u>	<u>58.1</u>	<u>55.7</u>
NT-6-G	<u>52.5</u>	<u>48.7</u>	44.6	44.6	44.6	44.6	44.6	<u>48.7</u>	<u>52.5</u>	<u>55.7</u>	<u>58.1</u>	<u>55.7</u>

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663 **Table. 6** Scope of symmetrical ultrasonic testing method

v_s (m/s)	v_c (m/s)	Minimum of central angle ($^\circ$)	Maximum of central angle ($^\circ$)
5620	4000	12	22
	4200	12	45
	4400	12	68
	4600	12	91
	4800	12	110
	5000	12	130
	5200	12	150
	5400	12	172

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