Development and Application of Non-Destructive Inspection for Steel-Concrete Composite Structures

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Steel-concrete composite structures, such as steel-concrete composite slabs and rigid connections between piers and beams, have been widely adopted in recent years due to their durability and economic efficiency. However, it is impossible to examine the boundary between steel plates and concrete visually after concrete casting because of the presence of steel plates surrounding the concrete. To solve this issue, a method to discriminate between filled and unfilled areas in concrete using low-frequency ultrasound has been developed and its application to actual bridges has commenced.

1. Introduction

In recent years, steel-concrete composite structures have been widely adopted in bridge construction due to their durability and cost efficiency. Examples include steel-concrete composite slabs and rigid connections between piers and beams. The steel-concrete composite structures must be completely filled with concrete in order for them to have their required strength and enhance the durability of the bridge. However, the steel plate makes it impossible to visually verify how evenly the concrete casting has performed.

With reference to the steel-concrete composite slab (hereinafter called composite slab)(1) shown in **Fig. 1**, any parts left unfilled after construction, including gaps and honeycombs, would allow rain infiltration into the slab, posing the risk of diminished durability as a result of corrosion of reinforcing members (e.g., ribs, studs, and channels) or steel bottom plates.

As for the rigid connection between a reinforced concrete pier and a beam (hereinafter called rigid connection) shown in **Fig. 2**, the direction of concrete casting tends to cause gaps on the bottom surface of the steel plate flange. In addition, the thickness of the steel plate (25-100 mm) makes it difficult to perform simple testing methods such as hammering inspections.(2), (3)

To solve these issues the methods for detecting unfilled parts in steel-concrete interface, focusing on low-frequency ultrasound have been developed.

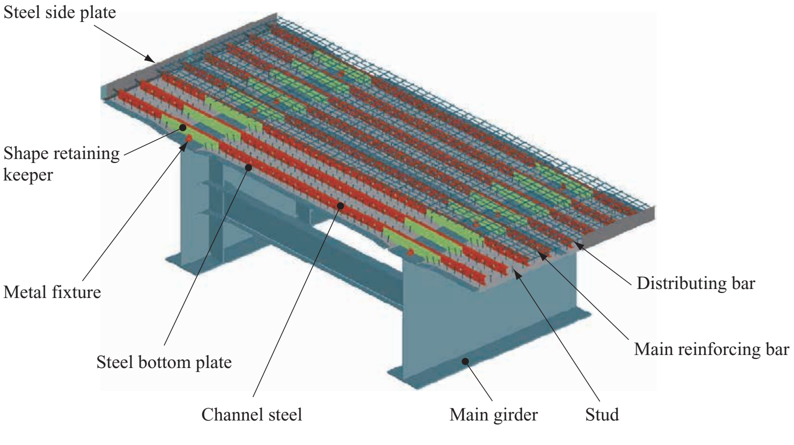


Fig. 1 Schematic view of the steel-concrete composite slab

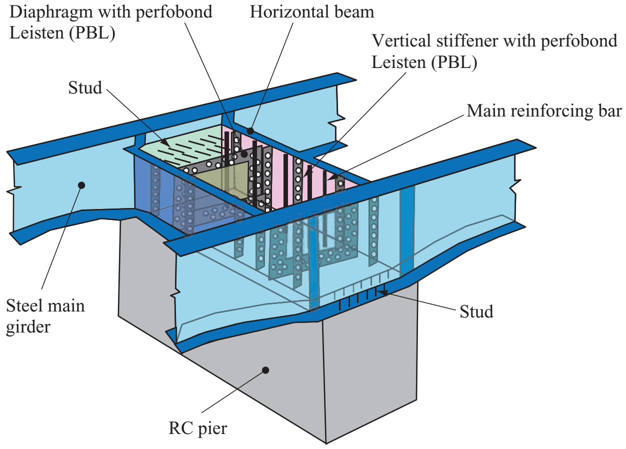


Fig. 2 Schematic view of the rigid connections between a reinforced concrete pier and a steel beam

This paper provides an overview of the techniques and presents its application to composite slabs actually used in bridges.

2. Overview of ultrasonic testing technique

2.1 Ultrasonic testing for concrete

Ultrasonic testing (UT), one type of nondestructive testing methods, is suited to inspecting the inner condition of materials. It has been widely applied in industrial fields for steel weld inspection and steel quality examination.(4) For concrete structures, UT is used to measure sound velocity, slab thickness, and depth of cracking, as well as for estimating strength. Although 2-5 MHz ultrasound is normally used in UT for metallic materials, 50-500 kHz ultrasound is used for concrete because it is a porous composite material made of cement paste and aggregates.(5) Acoustic properties of concrete which depend on the material properties and the age of the concrete must also be taken into consideration in the case of estimation by UT.

2.2 Development of testing and evaluation techniques for composite slabs

2.2.1 Principle of the developed technique

Steel bottom plates used for composite slabs are commonly as thin as 6-9 mm. **Figure 3** is a schematic illustration of the ultrasound which is transmitted from the steel plate in a thin steel-concrete composite structure.

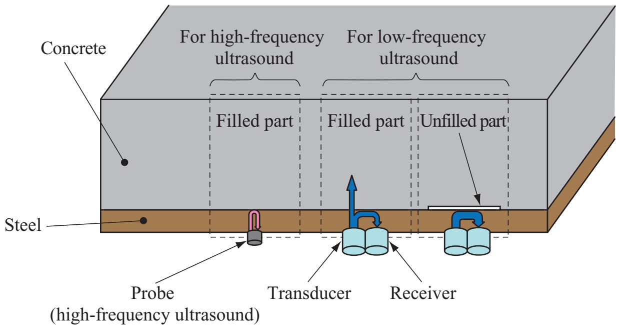


Fig. 3 Propagation of ultrasound in thin steel-concrete composite structures

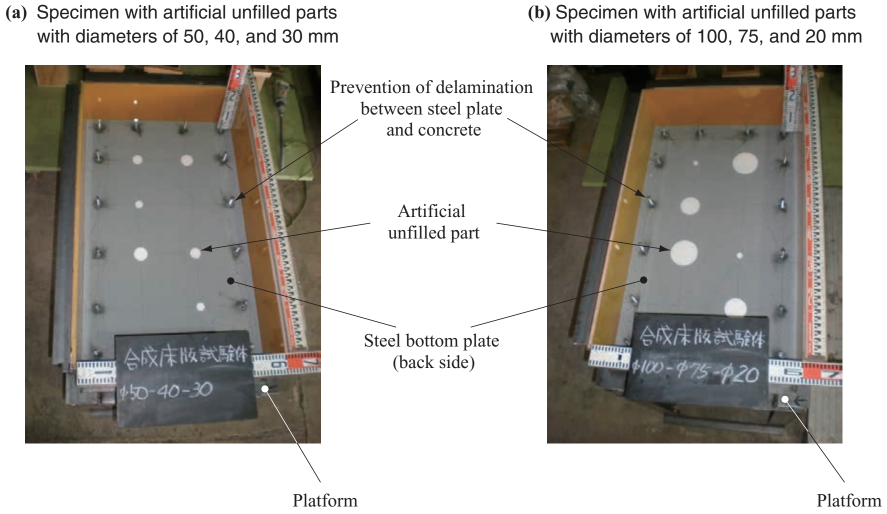
The normal approach for examining the state of a steel-concrete interface from the bottom plate side would be to apply high frequency ultrasound on the order of MHz, which has a shorter wavelength than the thickness of the steel plate and enables the resolution to be enhanced to distinguish the boundary between the steel plate and concrete. However, as mentioned before, high frequency ultrasound does not easily transmit through concrete and would indicate little difference between the filled and unfilled parts. Therefore, this type of UT requires the use of low-frequency ultrasound (around 50 kHz to 1 MHz) that transmit fully through the concrete.

A double-probe straight-beam technique was used instead of a single-probe straight-beam technique because the back wall echo of the thin steel plate would be in the dead zone if the latter is used with low-frequency ultrasound. The low-frequency ultrasound transmitted to the thin steel plate propagates mainly as lamb waves while repeating multiple reflections, mode conversions, and interference. In a filled part, multiple reflection and propagation lamb waves weaken because a part of the ultrasound goes through the concrete. On the other hand, in an unfilled part, a lot of reflection echo is observed due to the total reflection at the unfilled part.(6) Thus, this difference enables the detection of unfilled parts in the steel-concrete.

2.2.2 Demonstration test

For an empirical demonstration of this principle, specimens were prepared to represent composite slabs. **Figure 4** shows overall views of the specimens before concrete casting. The steel plates have a thickness of 8 mm. An inorganic zinc rich primer was applied as a coating on the contact surface of the steel plate with concrete, and the test surface was coated with C-5 (heavy-duty coating). Unfilled parts were simulated by polystyrene foam with various sizes (thicknesses of 5 mm). The steel plate and concrete were integrated with M8-head bolts to prevent delamination after concrete hardened. **Figure 5** shows the positions where unfilled parts are intentionally allocated. Concrete casting was performed by using Ordinary Portland Cement to provide a designed compressive strength of 30 MPa by 28 days, a slump of 10 cm, maximum aggregate diameter of 20 mm, and slab thickness of 208 mm. The demonstration test was conducted after concrete hardened. The ultrasonic instrument and the probes used for this UT are shown in **Fig. 6**. Normal longitudinal wave probes with a frequency of 250 kHz including a transducer with a diameter of 38 mm were used.

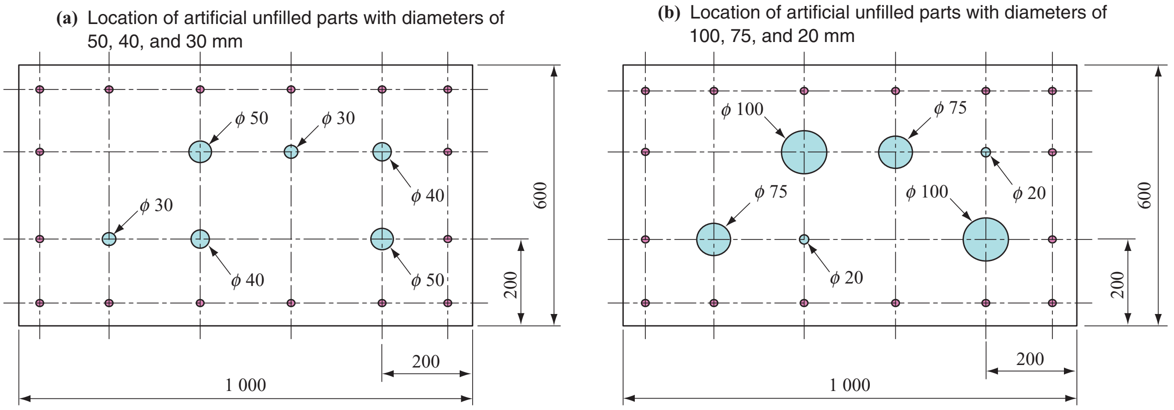
Figure 7 shows examples of ultrasound signals and **Fig. 8** shows the test results. The echo height becomes larger with increasing the diameter of unfilled parts up to 75 mm. According to the conditions for this test, the echo height remains almost constant when an unfilled part in the concrete has a size equivalent to 75 mm diameter or greater. This is because the unfilled area in the concrete is larger than the ultrasound beam width. If the unfilled area is smaller, it is possible to determine the size of the unfilled parts based on the echo height. This provides the


(a) Specimen with artificial unfilled parts with diameters of 50, 40, and 30 mm

(b) Specimen with artificial unfilled parts with diameters of 100, 75, and 20 mm

(Note)
1. Thickness of the steel bottom plate : 8 mm
2. Coating on the contact surface with concrete : Inorganic zinc rich primer
3. Coating on the test surface : C-5 (Heavy-duty coating)
4. Composite slab : Steel plate+concrete

Fig. 4 Specimens representing steel-concrete composite slabs (before concrete casting)


(a) Location of artificial unfilled parts with diameters of 50, 40, and 30 mm

(b) Location of artificial unfilled parts with diameters of 100, 75, and 20 mm

(Note) ○ : Artificial unfilled part (polystyrene foam with a thickness of 5 mm)
● : Prevention of delamination between the steel plate and concrete (M8 bolt)

Fig. 5 Configuration of artificial unfilled parts in specimens (unit:mm)

Fig. 6 Ultrasonic instrument and probes

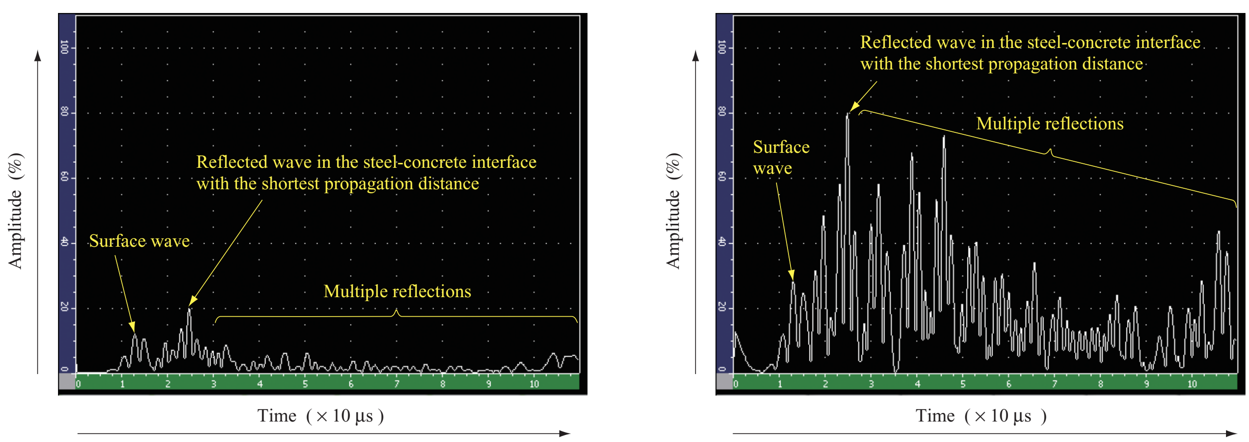
quantitative estimation of the unfilled parts, although the correlation between echo heights and the size of unfilled parts depends on the frequency of the ultrasound.

2.2.3 Preparing an ultrasonic testing aid

In actual bridges UT is conducted by overhead position testing from the inspection path. Due to such a posture is unstable for conducting the tests, the measurement values might be less repeatable than the tests conducted when looking down. Also, testing for a long period of time puts a heavy burden on workers. So, an ultrasonic testing aid was made as shown in **Fig. 9**. Referring to **Fig. 8**, ○ marks represent the test results by manual UT and ● marks represent the results obtained by using the ultrasonic testing aid. The repeatability of the test results was improved as more stable contact of the probes was achieved by using this aid.

2.2.4 Ultrasonic testing in an actual bridge

Normally, UT is conducted after setting the instrument gain with JIS standard blocks or the other reference blocks



(a) Filled part

(b) Artificial unfilled part with a diameter of 100 mm

Fig. 7 Example of ultrasound signals

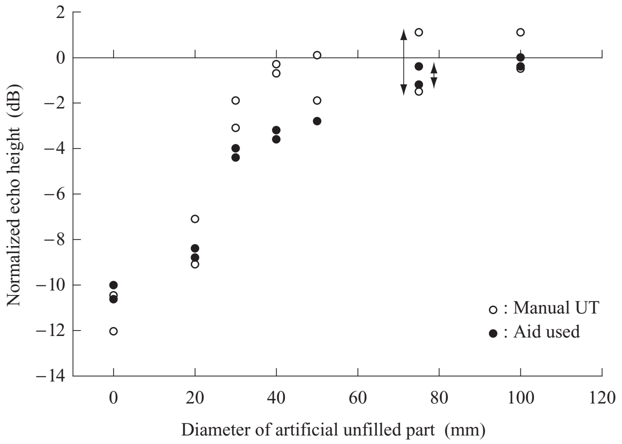


Fig. 8 Correlation between echo heights and artificial flaws in the specimens representing steel-concrete composite slabs

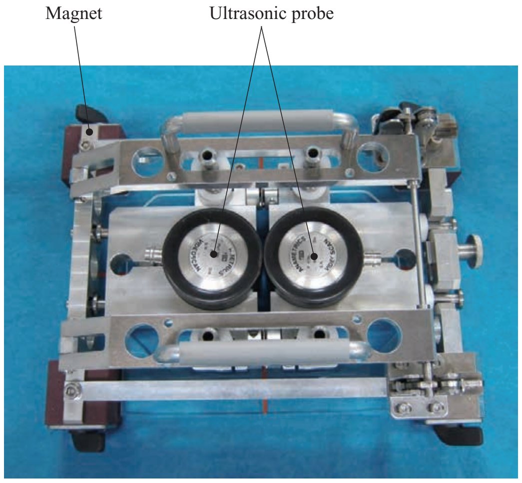


Fig. 9 Ultrasonic testing aid

to ensure the same flaw detection performance without dependent on the engineers in charge, date and time of testing, and so forth.

In this inspection for a composite slab, a reference steel plate block made of the same material with the same thickness and coating as the actual bridge was used for the calibration. The intensity of the reflection from the reference block assumes to that from an unfilled area, which is sufficiently larger than the ultrasound beam width. The standard gain was set so that the above-mentioned intensity became 80% on the display of the instrument before testing at each inspection area.

Inspection areas in the actual bridge and a view of the inspection are shown in **Figs. 10** and **11**, respectively. The intensity of the reflection from the steel-concrete interface in every inspection area marked below –4 dB and therefore satisfied the acceptance criterion. Thus, it was confirmed that they were sufficiently filled with concrete.

2.3 Study of testing and evaluation techniques for rigid connections

2.3.1 Principle of the developed technique

The thicknesses of steel plates used in rigid connections, which vary according to the required strength, are often 30-75 mm. The ultrasound beam spreads with increasing the beam path length. In such a situation, the flaw echo height is proportional to the area of the flaw when the flaws are smaller than the beam width. For this reason, increase in the propagation distance causes to a larger difference between the flaw echo (finite plane) and the boundary echo (infinite plane) as shown in **Fig. 12**.

At the steel-concrete interface of a filled part, about 30% of the ultrasound transmits through the concrete and the

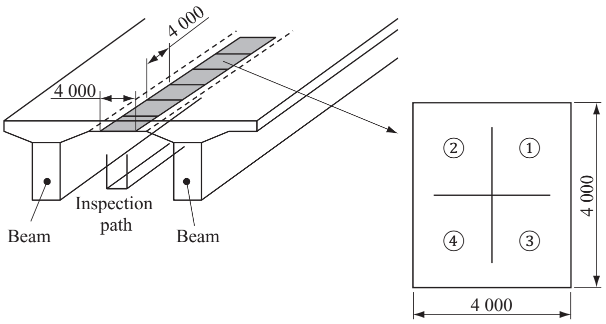


Fig. 10 Inspection area in the actual bridge (unit:mm)

Fig. 11 Inspection under actual conditions from the bottom steel plate

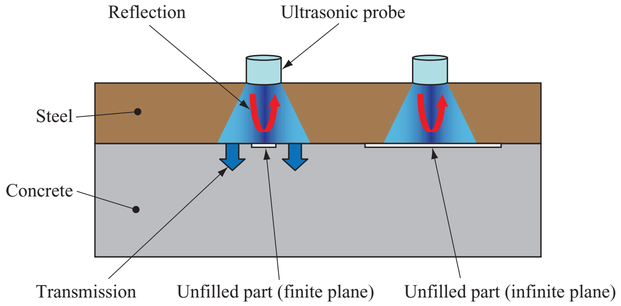


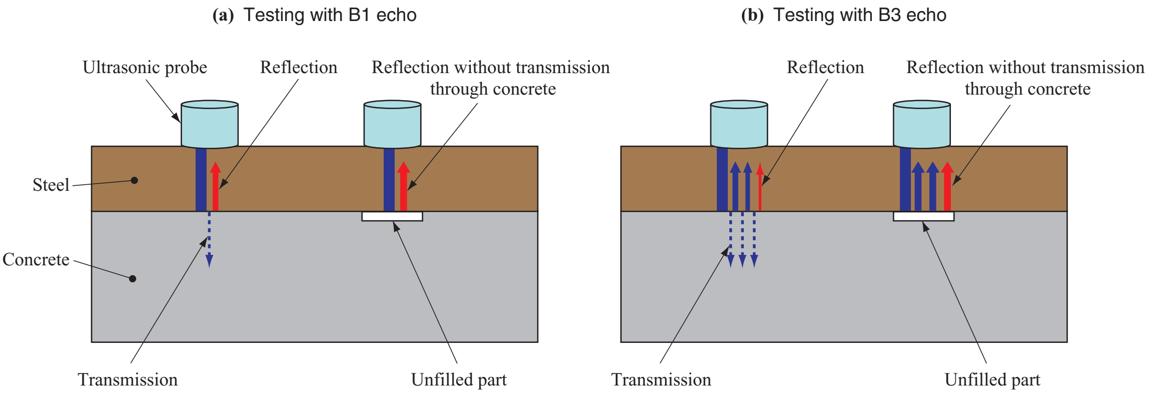
Fig. 12 Difference between ultrasound reflections depending on flaw sizes

remaining 70% reflects back due to the difference in the acoustic impedance. **Figure 13** shows how the number of reflections on the steel-concrete interface influences the ultrasonic echo height. The reflected ultrasonic echo height gradually diminishes with each reflection on the interface as 30% of the wave transmits through the concrete. This idea of focusing on the ultrasonic echo after several reflections on the steel-concrete interface is expected to be used to verify how evenly the concrete has filled the cavity even through a thick steel plate.

2.3.2 Demonstration test

For empirical demonstration of this principle, specimens were prepared to represent rigid connections. **Figure 14** shows overall views of the specimens. After installing a steel plate flange with a thickness of 75 mm, casting was performed in two steps with self-compacting concrete (designed compressive strength of 36 MPa by 28 days) and press-fit self-compacting mortar. Two castings were performed: steel overlay concrete casting and steel underlay concrete casting. The steel underlay concrete casting was used to understand how the excessive air influence on the detectability of flaws. In either case, the test was conducted after concrete hardened. The same ultrasonic instrument as shown in **Fig. 6** was used for the UT while ultrasonic probes with frequencies of 500 kHz and a transducer with diameters of 25.4 mm were used.

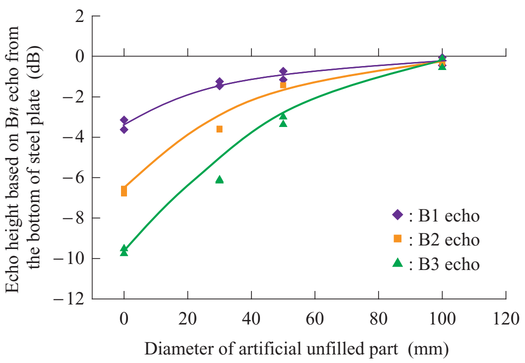
Figure 15 shows a example of ultrasound signals and



(a) Testing with B1 echo

(b) Testing with B3 echo

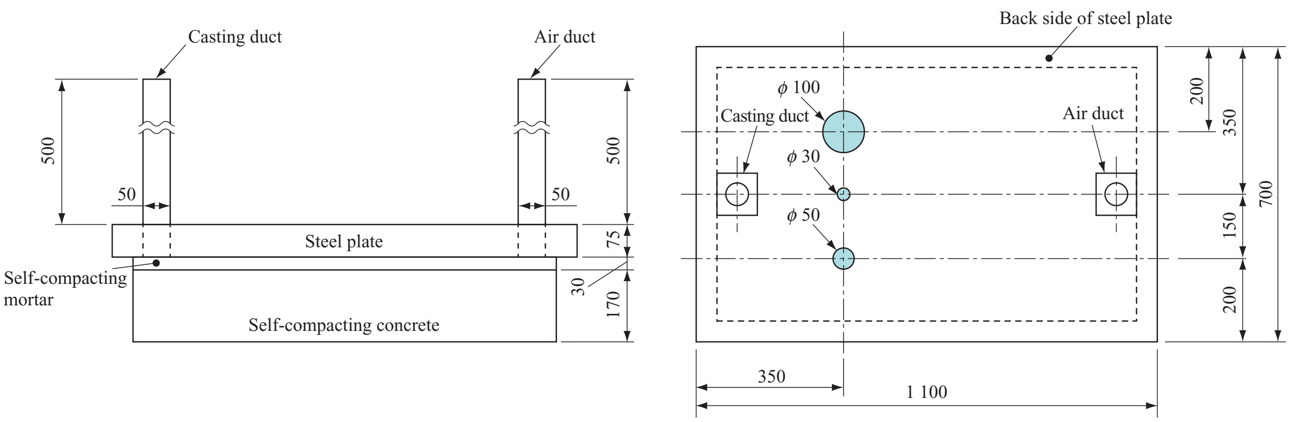
(c) Change in echo height corresponding to B*n* echo (*n* = 1–3)



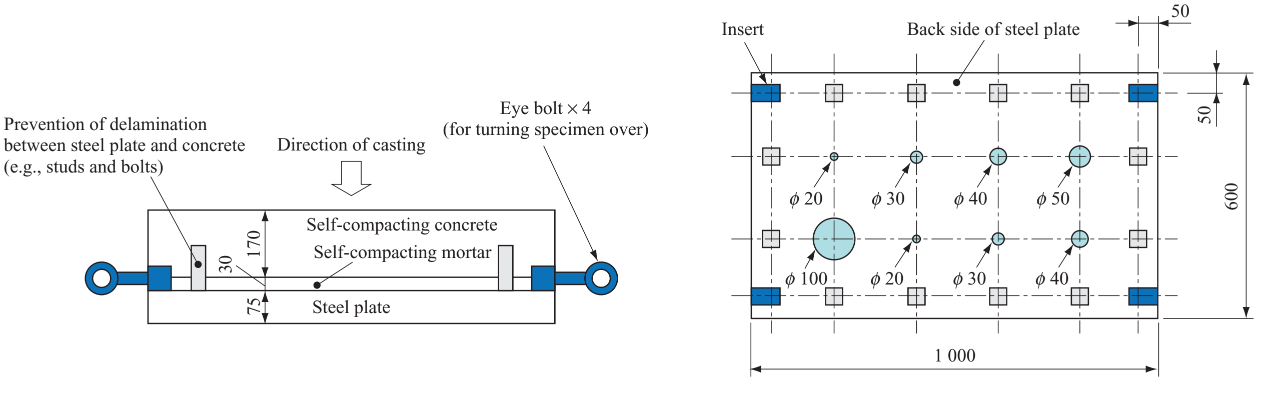
(Note) Data corresponding to probes with a frequency of 250 kHz including a transducer with a diameter of 38 mm are used.

Fig. 13 Ultrasound echo height at the boundary between the steel plate and concrete affected by reflection times

(a) Steel overlay specimen



(b) Steel underlay specimen



(Note) ● : Artificial unfilled part (foamed polystyrene with a thickness of 5 mm)

Fig. 14 Specimens representing rigid connections between a reinforced concrete pier and a steel beam (unit:mm)

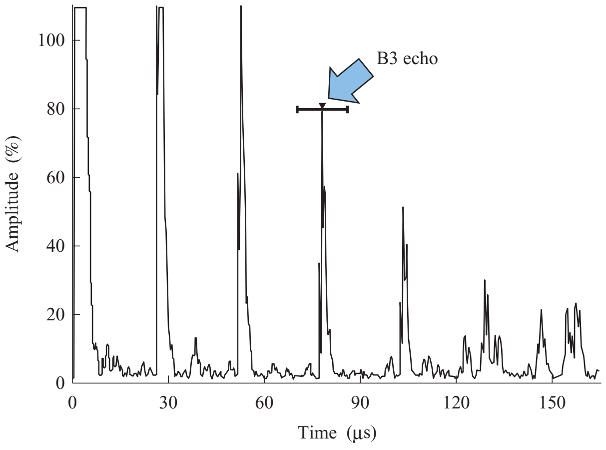
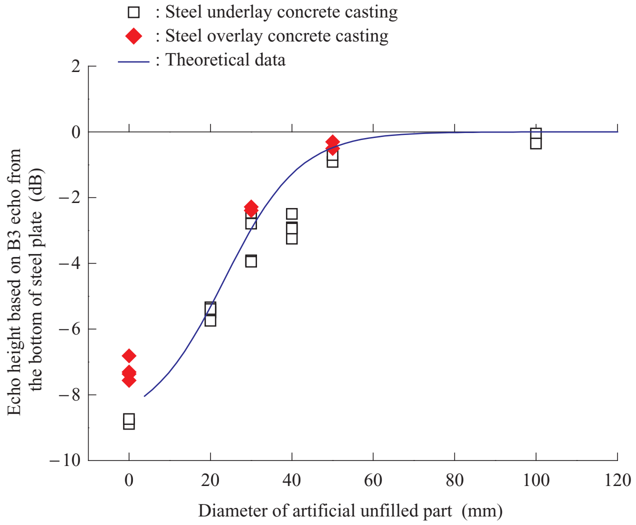


Fig. 15 Example of ultrasound signals

Fig. 16 shows the test results. Due to concern about the greater impact of electrical noise as a result of higher device gain, evaluation was made with ultrasonic echoes after three reflections on the steel-concrete interface (B3 echo). The echo height of a B3 echo becomes larger with increasing the diameter of unfilled parts up to 50 mm.



(Note) Theoretical data were calculated based on the following values.
- Fine aggregates : Density 2.6 g/cm^3, Elastic modulus 60 kN/mm^2, Diameter 1.2 mm, Mixing rate 0.43
- Cement paste : Density 2.0 g/cm^3, Elastic modulus 22.5 kN/mm^2

Fig. 16 Correlation between echo heights and artificial flaws in the specimens representing rigid connections between the RC pier and the steel beam

Comparison was made with the theoretical values of the echo height calculated from the model(7) using a DGS (Distance-Gain-Size) diagram that represents the correlation between the echo height of a round planar flaw and the propagation distance of the ultrasound while taking into account the scattering(8) caused by fine aggregates in self-compacting mortar. As a result, it provided that the test result was good agreement with theoretical values. It was also observed that steel overlay concrete casting tended to present relatively higher echo height as compared to steel underlay concrete casting both in properly filled areas and artificial unfilled areas because air rose up and gather at the bottom of the steel plate.

Further study will be made for optimizing the testing conditions so that this method will be applicable to different thicknesses of steel plates and sizes of unfilled areas that need to be detected.

3. Conclusion

This paper provides an overview of UT and evaluation techniques for detecting unfilled parts in steel-concrete composite structures, and presents an application to an actual bridge.

(1) Development of a testing and evaluation technique for composite slabs
  - A technique for detecting unfilled parts in a thin steel plate-concrete interface was developed by applying straight-beam technique with low-frequency ultrasound.
  - The demonstration test verified that the technique was able to identify unfilled areas with a size of 75 mm diameter or smaller under the conditions for this test.
  - The repeatability of UT was improved by using the ultrasonic testing aid.
  - An inspection was conducted with an actual bridge to confirm that it was sufficiently filled with concrete.

(2) Development of a testing and evaluation technique for rigid connections
  - A technique for detecting unfilled parts in a thick steel plate-concrete interface was developed by focusing on the B3 echo from the steel-concrete interface.
  - The test result showed good agreement with theoretical values calculated from a DGS diagram that took into account scattering from aggregates.

One of the tasks that lies ahead of us is to enhance the precision of quantitative evaluation so that it takes the actual hardening properties of concrete such as material age into account. The application of these techniques are not limited to examination of how well a structure is filled with concrete at construction. It can also be applied as a testing technique for supporting the decision of a repairing procedure once the structure comes into service, for example, for detecting delamination or water infiltration between the steel-concrete interface. It will be necessary to make more practical application to bridges and to expand applicable objects of these technologies.

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