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Research paper

Defect Estimation of Steel Fiber Reinforced Concrete Members Using the Impact Echo Method

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Abstract

Among fiber-reinforced composites, steel fiber strengthens concrete and makes up for brittleness, which is a weakness of the concrete material. For this reason, steel fiber is used to reduce the weight of concrete in order to enhance its strength. While it is a recent trend to use steel fiber reinforced concrete for silos, tunnels, etc., there are few studies on its quality management and applicability assessment. This study applies the non-destructive inspection method, which is a quality management instrument, to assess the quality management and applicability of steel fiber reinforced concrete. This study verifies the possibility and reliability of steel fiber reinforced concrete quality management by means of nondestructive test methods. In this experiment, the specimens are hollow column members with thicknesses of 100 mm, 150 mm and 200 mm and slab members with defect parameters of 120 mm, 200 mm and 240 mm. As 9 variables were applied to the experiment where hollow column members were used, the error rate of specimens whose design strength was 24 MPa was 4.0%, that of specimens whose design strength was 30 MPa 2.6%, and that of specimens whose design strength was 40 MPa 1.8%, respectively. As for specimens with defects inside, the error rate was 6.9%, 4.1%, and 3.7%, respectively. The average error rate of these was 3.8%, which indicates a relatively high level of reliability.

Keywords: *Concrete member, Defect, Estimation, Impact echo method, Steel fiber*

1. Introduction

Material disadvantages of ordinary concrete include low tensile strength and flexural strength, brittle behavior upon destruction, etc [1]. To make up for such weaknesses, many studies have been conducted on steel fiber reinforced concrete, etc. As steel fiber reinforced concrete enhances concrete tensile strength and reduces brittle behavior, it can reduce concrete weight and improves mechanical properties at the same time. Among fiber-reinforced composites, steel fiber strengthens concrete and makes up for brittleness, which is a weakness of the concrete material. For this reason, steel fiber is used to reduce the weight of concrete in order to enhance its strength. While it is a recent trend to use steel fiber reinforced concrete for silos, tunnels, etc., there are few studies on its quality management and applicability assessment.

This study applies the nondestructive inspection method, which is a quality management instrument, to assess the quality management and applicability of steel fiber reinforced concrete. The nondestructive inspection method is different from the ordinary destructive inspection method, which destructs or cuts off a member of a building to facilitate the inspection of the inside when a problem, such as crevice, heterogeneous substance, etc., occurs [2]. This inspection method, however, examines defects, stress, characteristics, material change, integrity, etc., inside or outside a building by using radiation, ultrasound, electromagnetism, liquid, heat, light, etc., without changing or destructing its material properties or internal structures. It causes no destruction to materials. The non-destructive inspection method, however, may produce different results depending on the inspection type, instrument, and data analysis method. S. U. Hong and Y. S. Cho [3] sought to estimate positions of reinforcing rods, steel sheets, and PVC pipes inside a slab section in order to detect damage of an ordinary concrete structure. Jaemo Kang, Seokmin Song, Duhee Park, and Changho Choi [4] examined the applicability of such estimation methods to detect defects around drainpipes. P.-L. Liu, L.-C. Lin, Y.-Y. Hsu, C.-Y. Yeh, P.-L. Yeh [5] conducted a study on how to distinguish reinforcing rods from cracks based on the analysis of impact echo phases. Mouhcine Benaicha, Olivier Jalbaud, Adil Hafidi Alaoui, and Yves Burtschell [6] examined the correlation between steel fiber reinforced concrete and ultrasonic wave speed. Job Thomas and Ananth Ramaswamy [7] examined mechanical properties of steel fiber reinforced concrete. KyoungChul Kim, InHwan Yang, and ChangBin Joh [8] investigated flexural behavior characteristics of steel fiber reinforced ultra-high-performance concrete members. HyunKi Choi, BaekIl Bae, and HaeShik Koo [9] analyzed the relation between concrete compressive strength and tensile strength depending on the steel fiber mixing ratio. Jacek Domski [10] examined the border between ordinary concrete and fiber reinforced concrete.

While many researchers have conducted studies that utilize nondestructive inspection methods in order to evaluate the performance of ordinary concrete, there has been no research on quality management of steel fiber reinforced concrete in application of nondestructive inspection methods. Nondestructive inspection methods for structure performance evaluation include the stress wave-based surface-wave

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method, impact-echo method, pulse echo method, impulse response method, etc. Among these, the impact echo method is a type of non-destructive inspection method used to investigate defects and cracks of concrete members. Advantages of impact echo method is the easiness of data analysis. It does not require a highly trained engineer to work and use the equipment, as well as analysis the data. A system can easily transfer the time domain data into frequency domain data. It has the ability to show close to real time results, which by simple analysis of the frequency data, one can come to estimation conclusions of concrete thickness [11]. When impact is applied to the surface of a specimen, the spherical wave front is transferred to the inside of the specimen (P, S waves). Surface waves (R waves) with a cylinder-shaped wave front may occur, being transferred through the surface of a specimen. It is possible to estimate the defects in the medium by using the impact echo method, the location of the interface, and the failure of the concrete when the dimensions of the specimen are known. In addition, when the propagation velocity of the P wave is known, the position of the continuous surface inside the test body can be grasped by measuring the arrival time of the reflected wave. In this study, a hollow column specimen with thickness of 100mm, 150mm and 200mm and a slab member with defects of 120mm, 200mm and 240mm were fabricated and tested. The impact-echo method, which is a type of nondestructive inspection method, is then used to estimate positions of the defects and crevices as well as the thickness of hollow column members of steel fiber reinforced concrete in order to verify its possibility and reliability of quality management.

2. Impact echo method

The impact-echo method utilizes temporary stress waves generated by elastic impact. When impact is applied to the surface of a specimen, the spherical wave front is transferred to the inside of the specimen. Surface waves with a cylinder-shaped wave front may occur, being transferred through the surface of a specimen. When a body wave encounters a discontinuum, such as crack or crevice or a border between heterogeneous layers, it reflects off and returns to the surface where stress waves were generated. The extent of surface displacement by compressional waves that result from a discontinuum inside a medium such as crack and crevice or compressional waves reflecting off the border between heterogeneous layers is far larger than that by shear waves. For this reason, waveforms detected on the surface are those by reflected compressional waves. When an impact is applied on a testing surface like concrete, the surface of concrete causes a P-wave (compression wave), V_p, a S-wave (shear wave), V_s, which propagates along spherical wave fronts through the structure, and a Rayleigh (surface wave), V_r, which propagates along circular wave fronts on the surface of the structure. The P-and S-waves are reflected from internal flaws and external free boundaries. The accelerations caused by the arrival of these stress waves are collected using a transducer near the location of impact and are used to compute the depth of free boundaries inside the structures and external free boundaries. In the Impact Echo test, the surface accelerations which were caused by compression waves form a resonance condition and show the maximum amplitude. It is possible to grasp the positions of boundaries or defects inside a medium by means of the impact-echo method. If the dimensions of the concrete member are known, it is possible to estimate specific defects of concrete. When the propagation speed of compression wave is known, it is possible to grasp the position of the continuing surface inside a specimen by measuring the arrival time of reflected waves. In a domain time that is obtainable by collecting stress waves from a vibration source by means of an accelerometer, the records are converted into a frequency domain using the fast Fourier transform (FFT).
As a result, the frequency of the first mode becomes that of the peak amplitude. Based on this data, it is possible to easily acquire the frequency of multiple reflections and to calculate the speed of compressive waves accordingly, the distance up to the reflective boundary of a plate structure, d ; speed of compression wave: V_p, and resonance frequency: f. A possible approximate solution may be Expression (1) below:

$$d = \frac{V_p}{2f} \quad (1)$$

Among stress waves propagated through media upon elastic impact, body waves are propagated through the inside of a medium by the compression and tension of medium particles (P waves) or shear movements right and left or up and down (S waves). Surface waves (R waves) occur when a medium has a free surface similar to the ground surface. The particles of compressional waves (P waves) move forward and backward in a parallel direction of wave progress, causing bulk strain with no shear strain. Particles of shear waves (S waves) cause shear strain with no bulk strain. When displacement in an axial direction is restrained, the speed of compressive waves (v_p) is determined by Expression (2) in consideration of the medium's elastic modulus and density.

$$v_p = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}} \quad (2)$$

Where, M: constrained modulus, E: Young's modulus, ρ : density, v : Poisson’s ratio

3. Experiment

In this experiment, steel fiber reinforced concrete members with crevices and defects are buried as deep as 100 mm, 120 mm, 200 mm, and 240 mm from the surface as shown in Table 1, Table 2, Figure 1 and Photo 1.

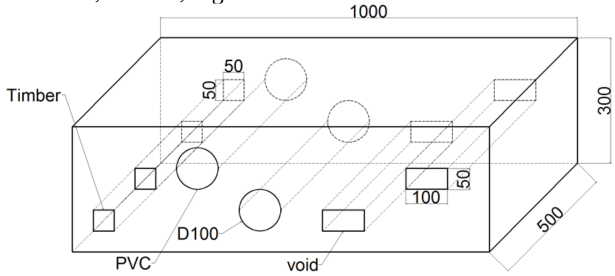

Fig. 1: Specimen with defects (mm)

Photo 1: Form of buried defect type

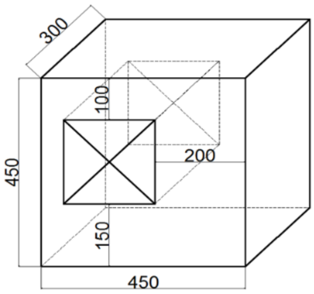

Fig. 2: Hollow column member

The impact-echo method, which is a type of non-destructive inspection method, is then used to estimate positions of the defects and crevices as well as the thickness of hollow column members of steel fiber reinforced concrete in order to verify its possibility and reliability of quality management. To this end, specimens were designed and produced as shown in Table 1, Figure 2 and Photo 2.

To estimate the thickness of hollow column members of steel fiber reinforced concrete and the positions of defects by means of the impact-echo method as shown in Photo 2, an experiment was conducted in accordance with ASTM C 1384-04.

Table 1: Specimen list

No / Variable name					
1	SFRC24D100	9	SFRC30D100	17	SFRC40D100
2	SFRC24D150	10	SFRC30D150	18	SFRC40D150
3	SFRC24D200	11	SFRC30D200	19	SFRC40D200
4	SFRC24V120	12	SFRC30V120	20	SFRC40V120
5	SFRC24V240	13	SFRC30V240	21	SFRC40V240
6	SFRC24P200	14	SFRC30P200	22	SFRC40P200
7	SFRC24T120	15	SFRC30T120	23	SFRC40T120
8	SFRC24T240	16	SFRC30T240	24	SFRC40T240
SFRC: Steel Fiber Reinforced Concrete Designed Strength [24 MPa, 30 MPa, 40 MPa] Damage [V: Void, P: Pipe, T: Timber] Location [100 mm, 120 mm, 150 mm, 200 mm, 240 mm]					

Table 2: Variable of defect

Variable		Size(mm)	Location(mm)
Depth	SFRC	450X300X450	100
			150
			200
Defect	Extruded Poly Styrene	50X100X500	120
			240
	PVC Pipe	R100X500	200
	Timber	50X50X500	120
			240

Photp 2: Depth estimation of SFRC hollow column

Fig. 3: Specimen of buried defect type

The process is on the followings. 1) Impact excitation test, 2) Record detected wave signal, 3) Convert time domain signal to frequency domain signal using the FFT (Fast Fourier Transform) method, 4) Calculate the peak frequency from frequency domain signal, 5) Calculate compressive wave velocity. In the experiment to estimate the thickness and defect positions of hollow column members, the error rate was calculated based on the 3 estimations at random locations of specimens as shown in Photo 2, Figure 3 and Figure 4. The reliability of estimation was also evaluated accordingly.

Fig. 4: Defect estimation of SFRC defect type

4. Experimental result

With variables inside the steel fiber reinforced concrete specimens, the mold was removed at the aging point of 28 days at random positions on the surface of hollow columns of steel fiber reinforced concrete.

An experiment was then conducted to estimate positions by means of the impact-echo method. The experiment was conducted 3 times at random locations of the specimens, and the average was calculated. The average error rate was also calculated for each variable, and the experimental result is presented in Table 3.

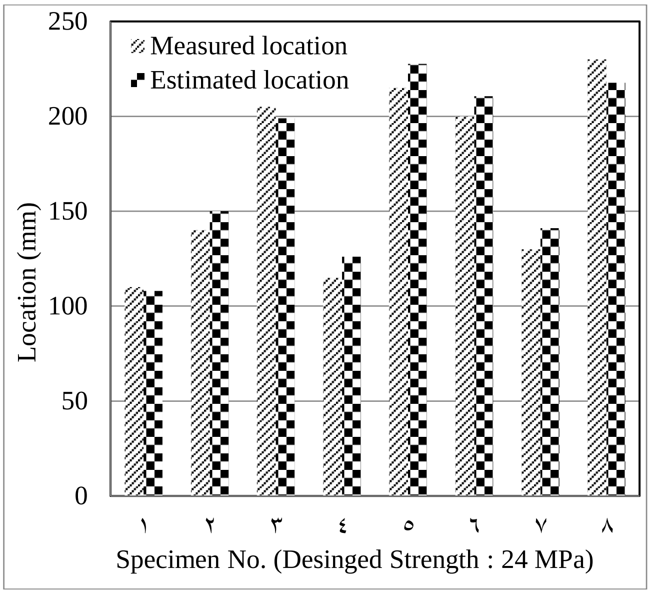

Fig. 5: Comparison results of estimation experiment (24 MPa)

As for specimens whose design strength was 24 MPa as shown in Figure 5, the design thickness of SFRC24D100, a hollow column member specimen of steel fiber reinforced concrete was 100 mm as shown in Table 3; however, the actual thickness was 110 mm because of the error in production. The thickness estimated by means of the impact-echo method was 108.00 mm, and the error rate was 1.8%. The design thickness of SFRC24D150 was 150 mm, and the actual thickness was 140 mm. The thickness estimated by means of the impact-echo method was 150.00 mm, and the error rate was 7.1%. The design thickness of SFRC24D200 was 200 mm, and the actual thickness was 205 mm. The thickness estimated by means of the impact-echo method was 199.00 mm, and the error rate was 2.9%. The general error rate of the thickness estimation of the steel fiber reinforced concrete (24 MPa) hollow column members in utilization of the impact-echo method was 4.0%, which is relatively accurate.

Figure 5 and Figure 6 compares the estimations and actual measurements when variables were applied to steel fiber reinforced concrete: The actual position of SFRC24V120 was 115 mm while the position estimated by means of the impact-echo method was 126.00 mm. The estimation error rate was 9.6%.

As for SFRC24V240, the actual position was 215 mm while the estimated position was 227.67 mm. The error rate was 5.9%. As for SFRC24P200, the actual position was 200 mm, and the estimated position was 210.67 mm. Thus, the error rate was 5.3%. As for SFRC24T120, the actual position was 130 mm, and the estimated position was 141.00 mm. Thus, the error rate was 8.5%. As for SFRC24T240, the actual position was 230 mm while the estimated position was 217.67 mm. Thus, the error rate was 5.4%. The average error rate was 6.9%.

Table 3: Experiment result

Variable name	Measured location	Estimated location			Average	Error ratio	Average of error ratio	
SFRC24D100	110	109	109	106	108.00	1.8	4.0	3.8
SFRC24D150	140	143	149	158	150.00	7.1		
SFRC24D200	205	199	203	195	199.00	2.9		
SFRC24V120	115	131	119	128	126.00	9.6	6.9	
SFRC24V240	215	244	213	226	227.67	5.9		
SFRC24P200	200	187	221	224	210.67	5.3		
SFRC24T120	130	151	117	155	141.00	8.5		
SFRC24T240	230	215	219	219	217.67	5.4		
SFRC30D100	105	111	103	95.9	103.30	1.6	2.6	
SFRC30D150	145	148	151	153	150.67	3.9		
SFRC30D200	197	190	187	201	192.67	2.2		
SFRC30V120	120	128	117	137	127.33	6.1	4.1	
SFRC30V240	200	202	193	205	200.00	0.0		
SFRC30P200	200	189	203	237	209.67	4.8		
SFRC30T120	130	111	143	115	123.00	5.4		
SFRC30T240	225	215	219	212	215.33	4.3		
SFRC40D100	106	106	109	106	107.00	0.9	1.8	
SFRC40D150	147	148	156	156	153.33	4.3		
SFRC40D200	203	205	210	194	203.00	0.0		
SFRC40V120	120	123	126	109	119.33	0.6	3.7	
SFRC40V240	220	199	199	212	203.33	7.6		
SFRC40P200	130	134	144	131	136.33	4.9		
SFRC40T120	130	140	135	126	133.67	2.8		
SFRC40T240	220	215	215	212	214.00	2.7		

As for specimens whose design strength was 30 MPa as shown in Figure 7, the design thickness of SFRC30D100, a hollow column member specimen of steel fiber reinforced concrete was 100 mm as shown in Table 3; however, the actual thickness was 105 mm because of the error in production. The thickness estimated by means of the impact-echo method was 103.30 mm, and the error rate was 1.6%. The design thickness of SFRC30D150 was 150 mm, and the actual thickness was 145 mm. The thickness estimated by means of the impact-echo method was 150.67 mm, and the error rate was 3.9%. The design thickness of SFRC30D200 was 200 mm, and the actual thickness was 197 mm.

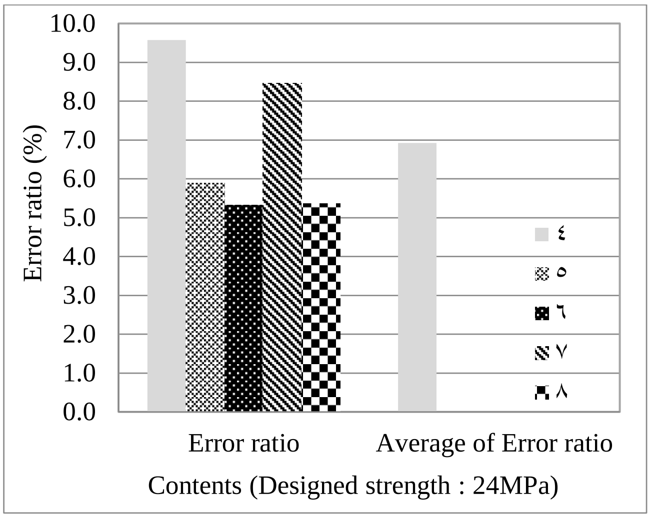

Fig. 6: Comparison error ratio of estimation of defect location (24MPa)

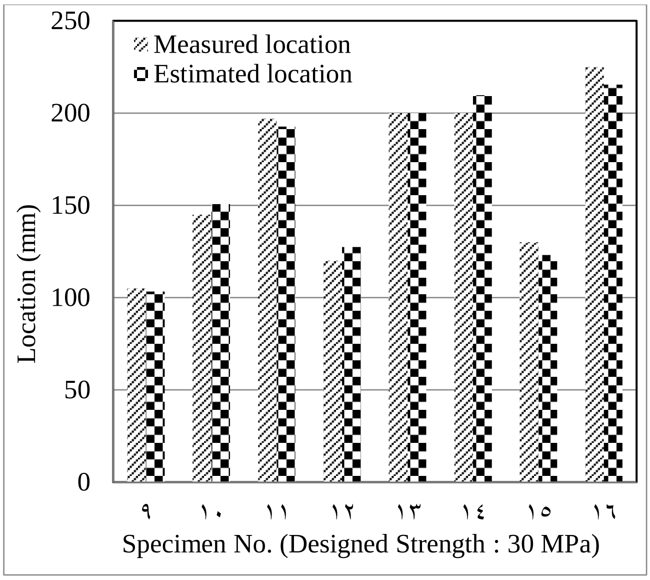

Fig. 7: Comparison results of estimation experiment (30 MPa)

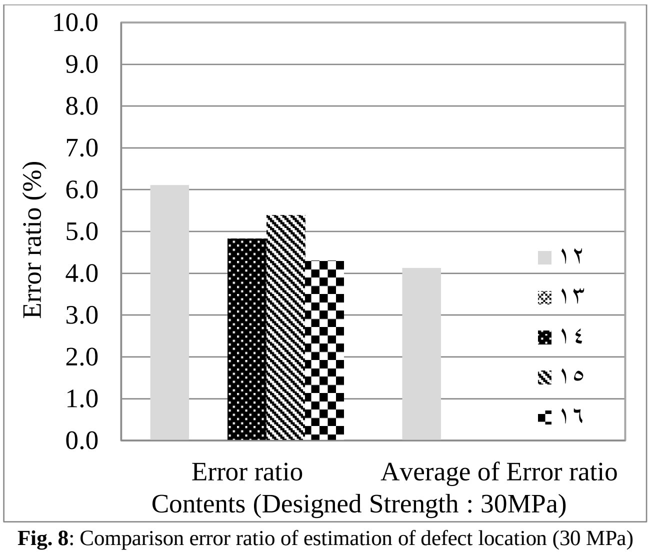

Fig. 8: Comparison error ratio of estimation of defect location (30 MPa)

The thickness estimated by means of the impact-echo method was 192.67 mm, and the error rate was 2.2%. The general error rate of the thickness estimation of the steel fiber reinforced concrete (30 MPa) hollow column members in utilization of the impact-echo method was 2.6%, which is relatively accurate. The error rate of SFRC30V120 was 6.1%; that of SFRC30V240 0.0%, and that of SFRC30P200 4.8%, that of SFRC30T120 5.4%, and that of SFRC30T240 4.3%, respectively. The average error rate was 4.1%.
As for specimens whose design strength was 40 MPa as shown in Figure 9, the design thickness of SFRC40D100, a hollow column member specimen of steel fiber reinforced concrete was 100 mm as shown in Table 3; however, the actual thickness was 106 mm because of the error in production. The thickness estimated by means of the impact-echo method was 107.00 mm, and the error rate was 0.9%. The design thickness of SFRC40D150 was 150 mm, and the actual thickness was 147 mm. The thickness estimated by means of the impact-echo method was 153.33 mm, and the error rate was 4.3%. The design thickness of SFRC40D200 was 200 mm, and the actual thickness was 203 mm. The thickness estimated by means of the impact-echo method was 203.00 mm, and the error rate was 0.0%. The general error rate of the thickness estimation of the steel fiber reinforced concrete (40 MPa) hollow column members in utilization of the impact-echo method was 1.8%, which is relatively accurate.

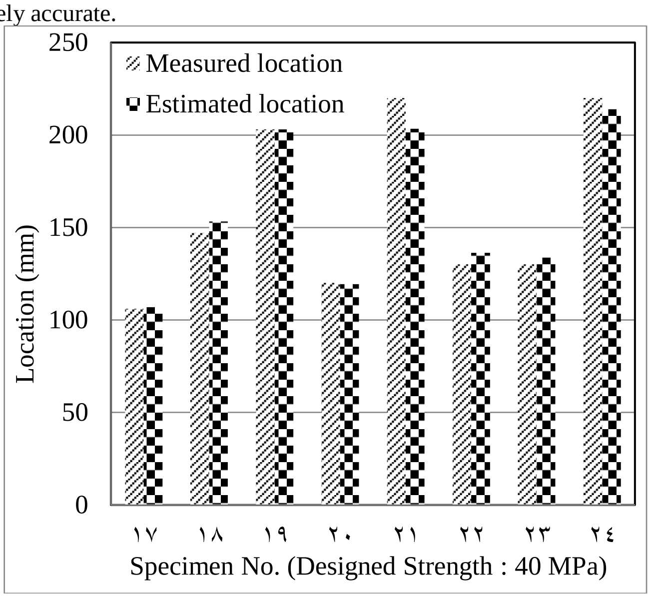

Fig. 9: Comparison results of estimation experiment (40 MPa)

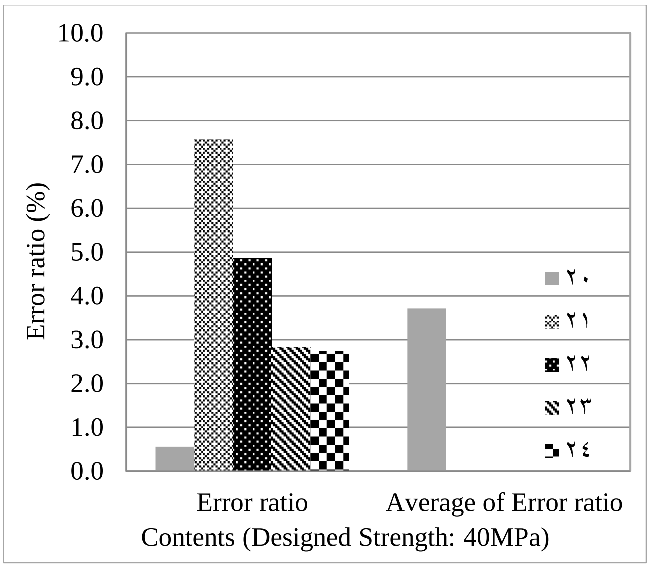

Fig. 10: Comparison error ratio of estimation of defect location (40 MPa)

As for specimens whose design strength was 40 MPa as shown in Figure 9 and Figure 10, the error rate of SFRC40V120 was 0.6% as shown in Table 3 and Figure 10. That of SFRC40V240 was 7.6%, that of SFRC40P200 4.9%, that of SFRC40T120d 2.8%, and the error rate of SFRC40T240 2.7%, respectively. The general error rate was 3.7%. The average error rate of estimation of 24 variables was 3.8%, which indicates that the reliability was relatively high.

5. Conclusion

The objective of this study was to verify the reliability of non-destructive inspection methods by estimating variables such as defects or crevices inside steel fiber reinforced concrete, thickness, etc. by means of the impact-echo method, which is a type of non-destructive inspection method. As 24 variables were applied to the experiment where hollow column members were used, the error rate of specimens whose design strength was 24 MPa was 4.0%, that of specimens whose design strength was 30 MPa 2.6%, and that of specimens whose

design strength was 40 MPa 1.8%, respectively. As for specimens with defects inside, the error rate was 6.9%, 4.1%, and 3.7%, respectively. The average error rate of these was 3.8%, which indicates a relatively high level of reliability.
This study verifies that the impact-echo method, which is a type of non-destructive inspection method, can be utilized to manage and maintain structures or facilities as it is effective in estimating the size of steel fiber reinforced concrete column members and the positions of defects inside concrete.

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