Investment (FII) Report, Vancouver.
Hashemi, A., Zarnani, P., Masoudnia, R., and Quenneville, P. (2018) "Experimental testing of rocking cross-laminated timber walls with resilient slip friction joints." *Journal of Structural Engineering*, ASCE, Vol. 144, No. 1, 10.1061/(ASCE)ST.1943-541X.0001931.
Hashemi, A., Valadbeigi, A., Masoudnia, R., and Quenneville, P. (2016). "Seismic resistant cross laminated timber structures using an innovative resilient friction damping system." *Procs., New Zealand Society of Earthquake Engineering Annual Conference*, Paper 28, Christchurch, New Zealand.
Hristovski, V., Dujic, B., Stojmanovska, M., and Mircevska, V. (2013). "Full-scale shaking-table tests of xlam panel systems and numerical verification: specimen 1." Journal of Structural Engineering, ASCE, Vol. 139, No. 11, pp. 2010-2018, 10.1061/(ASCE)ST.1943-541X.0000754.
Kramer, A., Barbosa, A.R., and Sinha, A. (2016). "Performance of steel energy dissipaters connected to cross-laminated timber wall panels subjected to tension and cyclic loading." Journal of Structural Engineering, ASCE, Vol. 142, No. 4, 10.1061/(ASCE)ST.1943-541X.0001410.
Kurama, Y.C., Weldon, B.D., and Shen, Q. (2006). "Experimental evaluation of posttensioned hybrid coupled wall subassemblages." *Journal of Structural Engineering*, ASCE, Vol. 132, No. 7, pp. 1017-1029, 10.1061/(ASCE)0733-9445(2006)132:7(1017).
Loo, W.Y., Quenneville, P., and Chouw, N. (2016). "Rocking timber structure with slip-friction connectors conceptualized as a plastically deformable hinge within a multistory shear wall." Journal of Structural Engineering, ASCE, Vol. 142, No. 4, 10.1061/(ASCE)ST.1943-541X.0001387.
Palermo, A., Pampanin, S., Buchanan, A., and Newcombe, M. (2005). "Seismic design of multi-storey buildings using laminated veneer lumber (LVL)." *Procs., New Zealand Society of Earthquake Engineering Annual Conference*, Paper 14, Taupo, New Zealand.
Pei, S., Popovski, M., & van de Lindt, J. W. (2012). Seismic design of a multi-story cross laminated timber building based on component level testing. World, 15, 19.
Popovski, M., and Gavric, I. (2016). "Performance of a 2-story CLT house subjected to lateral loads." Journal of Structural Engineering, ASCE, Vol. 142, No. 4, 10.1061/(ASCE)ST.1943-541X.0001315.
Popovski, M., Schneider, J., and Schweinsteiger (2010). "Lateral load resistance of cross-laminated wood panels." Procs., World Conference on Timber Engineering, June 20-24, Riva del Garda, Italy.
Sarti, F., Palermo, A., and Pampanin, S. (2016). "Quasi-static cyclic testing of two-thirds scale unbonded posttensioned rocking dissipative timber walls." Journal of Structural Engineering, ASCE, Vol. 142, No. 4, 10.1061/(ASCE)ST.1943-541X.0001291.
Shen, Q., Kurama, Y. C., & Weldon, B. D. (2006). "Seismic design and analytical modeling of posttensioned hybrid coupled wall subassemblages." Journal of Structural Engineering, ASCE, Vol. 132, No. 7, pp. 1030-1040.
Smith, T., Ludwig, F., Pampanin, S., Fragiacomo, A., Deam, B.B. (2007). "Seismic response of hybrid-LVL coupled walls under quasi-static and pseudo-dynamic testing." Procs., New Zealand Society of Earthquake Engineering Annual Conference, Paper 60, Palmerston North, New Zealand.
Stojmanovska, M., and Hristovski, V. (2008). "Experimental and analytical investigations of solid wooden wall panel elements subjected to lateral loads." *Procs., World Conference on*

Earthquake Engineering, October 12-17, Beijing, China.
Sustersic, I., Fragiacomo, M., and Dujic, B. (2016). “Seismic analysis of cross-laminated multistory timber buildings using code-prescribed methods: influence of panel size, connection ductility, and schematization.” Journal of Structural Engineering, ASCE, Vol. 142, No. 4, 10.1061/(ASCE)ST.1943-541X.0001344.
Yasumura, M., Kobayashi, K., Okabe, M., and Miyake, T. (2016). “Full-scale tests and numerical analysis of low-rise CLT structures under lateral loading.” Journal of Structural Engineering, ASCE, Vol. 142, No. 4, 10.1061/(ASCE)ST.1943-541X.0001348.

Investigative Assessment of Concrete Slab Using Non-Destructive Evaluation Techniques

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ABSTRACT

Concrete slabs are common members in building structures. Hardened concrete materials are strong in compression and relatively weak in tension and are used to withstand compressive stress in structures. Cracks in concrete occur when tensile stress exceeds the strength of concrete in tension. Significant cracks prompt the project stakeholders to question the integrity of the structure and to retain investigation teams to determine the extent of defects or distresses, identify potential causes, and assist in developing a remediation plan. Non-destructive evaluation (NDE) techniques have been gaining interests for field assessment. Properly conducted NDE shortens the time of assessment, saves cost, and provides information that is not visible to human eyes. The authors have served in many projects of structural assessment and realized the lack of knowledge on NDE techniques in the field. It is the intent of this study to discuss the advantages and limitations of NDE techniques. The projects presented include investigations of a reinforced concrete floor slab, concrete slab-on-grade system, a composite floor system, and a reinforced concrete pad foundation.

KEYWORDS: concrete slab, non-destructive testing, ground penetrating radar, ultrasonic echo tomography

INTRODUCTION

Concrete floor slabs present large surface area and are in contact with most of the interior architectural finishes and nonstructural members than other structural members. The users can visually observe construction defects in newly built slab systems and distresses of exiting slab systems which are reflected as cracks and separations in the architectural finishes and nonstructural members. Some construction defects of new concrete slab systems include significant cracks and honeycombing. Distresses in existing concrete slab systems include cracks, spalls, and delamination. Cracks are the most often observed signs of defects or distresses. Cracks may be the early signs of spall and delamination. Hardened concrete materials are strong in compression and relatively weak in tension and are used to withstand compressive loading in structures. Cracks in concrete occur when tensile stress exceeds the strength of concrete in tension. Some contributing factors include plastic or drying shrinkage, poor workmanship, overloading, corrosion, and subgrade soil movement. It has been noticed that increasing amount of research effort has been made to develop high performance concrete and ultrahigh performance concrete to reduce the chance of concrete cracking due to shrinkage, poor workmanship, and corrosion (Mindess et al. 2003; Li and Rangaraju 2015, 2016; Li 2016, 2017).

Investigation of construction defects in new slab systems and distresses in existing slab systems are often performed to determine potential contributing factors, evaluate the extent of distresses or defects, identify responsible parties, and develop a remediation plan. The direct approaches of investigation require destructive activities such as removing architecture finishes to expose structural members, digging test pit to access below grade members, and coring and cutting specimens from the slab systems for laboratory testing. The destructive approaches of investigation can be hit-and-miss processes, and are time-consuming, labor-intensive, and costly. Non-destructive evaluation (NDE) falls into indirect approaches of investigation. NDE measures properties of concrete that can be related to the properties of concrete in questions (Malhotra and Carino 2004). These properties of concrete can be determined by electrical testing, electromagnetic testing, and physical testing (Malhotra and Carino 2004; ACI 2003, 2013; De La Haza et al. 2013; Moczko et al. 2016; Li et al. 2018). NDE can reduce or eliminate the needs for destructive explorations and can be performed fast and cost efficiently. NDE technologies have been profoundly advanced in the past decade. This study discusses NDE technologies that can be used in the investigation of concrete slab systems. Project case studies are discussed to demonstrate the implementation of NDE in the assessments of buildings.

It should be noted that observations and measurements are never exact. As it is defined by the American Congress on Surveying and Mapping (ACSM 2005), an error is the difference between an observed value of a quantity and the ideal or true value of that quantity (ACSM 2005). The true value of quantity can never be known with exactness, with few exceptions that the true value can be known when it is (a) mathematically determinable which is independent of observation; (b) a conventional value established by authority (ACSM 2005). Typical sources of errors are natural errors, instrument errors, and personnel errors. Errors exist in any measurements. The measurements obtained by NDE techniques contain errors just as any measurements obtained by other measuring techniques. It is people who need to find a balance between cost and evaluation accuracy. As for example, the depth of a reinforcing-bar (rebar) from the top edge of the rebar to the top surface of a concrete slab is measured to be 50 mm by a ground penetrating radar. While the true depth may be 52 mm or 48 mm. A value of the depth very close to the true value of the depth may be obtained by exposing the rebar to measure. However, this loses the NDE's benefit of reducing the needs of destructive explorations.

NON-DESTRUCTIVE EVALUATION (NDE) METHODS

Ultrasonic Echo Tomography (UET) Methods: A stress-wave propagating in an isotropic medium is partly reflected when it reaches a second medium which has a different acoustic impedance than the first medium. The remainder penetrates into the second medium. Acoustic impedance is defined as the product of the medium's density and its acoustic velocity. Stress-waves propagating in a hardened concrete can be reflected at locations of voids, honeycombing, delamination, steel reinforcing bars and the back-side of the concrete member. Ultrasonic echo method records the time between shear-wave generated and the reflected shear-wave returned to locate the source of reflection in concrete. Ultrasonic Echo Tomography (UET) is a new and sophisticated type of ultrasonic echo method, which can send multiple shear-waves (48-channel tester is available in the market) into concrete for testing. The data obtained is then processed to create a 3-D model with a computer software to show the relative locations of objects in concrete.

Short Pulse Radar Methods: Similar to stress-wave propagation, an electromagnetic wave propagating in a material is partially reflected as it hits an interface with a second material which has a different dielectric constant. The more different in the dielectric constants of the two materials, the more energy reflected at the interface. In the 1960s, short-pulse radar was used to identify and profile subsurface geological features, which led to the fast development of ground penetrating radars which were commonly known as GPRs (Malhotra and Carino 2004). For application in building assessment, the authors have used a high-frequency GPR (around 1.6 GHz – 2.6 GHz) to detect shallow features such as rebars, delamination in concrete, and void space under slab-on-grade. This is based on the difference in the dielectric constants of air, concrete, and steel. A low-frequency GPR (around 0.3 GHz – 0.8 GHz) can be used to detect deep underground features such as utility lines, water table, and sinkholes.

a. Parallel cracks b. Random cracks c. Grid pattern cracks

Figure 1 Surface cracks observed throughout top surface of floor slab (Images by Zhengqi Li)

Impulse Response (Mobility) Test: This test involves using a handheld hammer to impact the concrete surface and generate transient stress waves in the concrete element. These waves set up vibrational modes, mostly flexural vibration, of the element near the test point (ASTM C1740 2016). The vibration of the element is recorded and analyzed in a form of mobility spectrum to detect anomalies of plate-like element including delamination, poorly consolidated concrete, regions of poor support or voids beneath slabs-on-grade. A reduction in plate thickness corresponds to a large increase in the mean mobility because flexural rigidity is proportional to thicknesses raised to the third power (ASTM C1740 2016). The tests are performed in a grid pattern with a spacing of 300 to 1800 mm (1 to 6 feet) which can cover a large surface area for evaluation. The impulse-response method is used for rapid screening of structures to identify potential locations of anomalous conditions that require detailed investigations such as ultrasonic echo tomography and intrusive coring or probing.

Interior Floor Relative Elevation Survey: Floor relative elevation survey is often performed inside a building as part of an assessment of foundation movement. A pressurized hydrostatic altimeter system filled with pressurized air consists of a measurement module and a reference cell which are connected by a flexible cable (e.g. 30-m long cable). The measurement module detects changes in the air pressure in the cable which is related to the relative height of the measurement module to the reference cell which stays at a same height during survey. This system allows surveying interior floor area of a building with the presence of furniture and partition walls where optical surveying system cannot be efficiently utilized. Contour plots are created to determine the profile of the floor surface.

CASE STUDIES

Composite Floor Slab: A three-story building to be used as a commercial storage facility was under construction in the state of New York. Its foundation system consisted of footings under columns and a slab-on-grade. The elevated floor slabs consisted of 50-mm (2-inch) concrete topping cast on corrugated metal deck. The concrete was about 100-mm (4-inch) thick at the valley portion of the metal deck. A welded wire mesh system with a spacing of 150 mm (6 inches) and a wire diameter of 3.4 mm (0.134 inches) in two directions was specified to be installed at the mid-height of the concrete topping. At about 2 days after concrete placement, random cracks, parallel cracks, and grid pattern cracks were observed at many locations throughout the top surface of the second-level floor slab. See Figure 1. The contractor had reported that a ride-on concrete finisher, instead of a walk-behind finisher, was used. In addition, the welded wire mesh was manually lifted at position during concrete placement.

Figure 2 Cracks on north side of concrete pad (Image by Zhengqi Li)

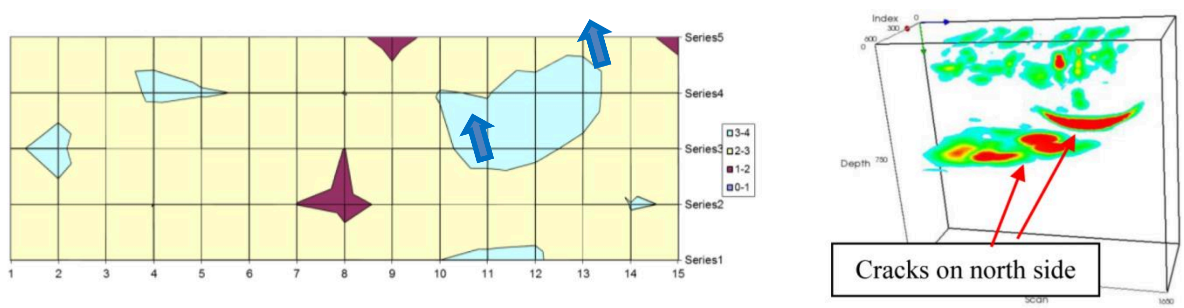
A visual condition assessment and a construction document review were conducted. Based on the information collected, it was anticipated that the cracks could possibly be attributed to shrinkage, concrete settlement over reinforcement, and overloading by using a ride-on concrete finisher. GPR survey was utilized in this project to determine the condition of the welded wire mesh in the concrete topping. It was observed from the GPR survey performed throughout the top side of floor slab that the welded wire mesh was installed near the bottom of the concrete topping (near top side of metal deck). Metal wire was detected under every crack of the grid pattern cracks. Concrete coring was conducted at 5 locations for compressive strength testing and petrographic analysis. It was observed from the 5 cores that, at 4 locations, the welded wire mesh was installed at 50-mm (2 inch) to 75-mm (2.5-inch) from top surface of concrete topping, which was consistent with the findings of GPR survey.

Welded wire mesh was used to control temperature and shrinkage cracking of concrete. The use of welded wire mesh has been recommended by American Concrete Institute (2015) and Steel Deck Institute (1987). In ACI 302.1R-15 “Guide to Concrete Floor and Slab Construction”, it is recommended to place the welded wire mesh near the top of the slab (ACI 2015). In SDI Publication No. 26 “Design Manual for Composite Decks, Form Decks and Roof Decks”, it is recommended to keep the wire mesh near the top of the slab with a 19-mm (¾-inch) to 25-mm (1-inch) cover (SDI 1987). In the present project, the welded wire mesh was specified to be installed at the mid-height of the concrete topping, which should be about 25 mm (1 inch) from concrete surface. The contractor did not follow appropriate practice, such as using mesh support/chair, to maintain the welded wire mesh at the correct position. This compromised the performance of wire mesh in controlling shrinkage crack. The ride-on concrete finisher had more weight than a walk-behind concrete finisher. This could have caused large deflection of the metal deck and contributed to the settlement cracks over metal wire (grid pattern cracks).

Concrete Foundation Pad Subjected to Fire: A steel silo structure collapsed due to a fire accident in the state of Texas. The silo structure's foundation consisted of drilled piles and a 4-feet thick concrete pad. After the debris were removed offsite, significant cracks were observed on the north side of the concrete pad. See Figure 2. The concrete pad was proposed to be reused for a new steel silo structure. A concrete condition assessment, which included determining the strength of concrete, detecting possible subsurface delamination and extent of crack observed on the side of the concrete pad, was performed. Fire damage related delamination and cracks are generally located near the surface that were exposed to high temperature (Mindess et al. 2003). Impulse response test was performed on the top surface of the concrete pad to detect possible signs of fire damaged concrete. To determine the extent of the cracks observed on the north side of concrete pad, UET was performed from the top side of concrete pad.

A study of the historical information of the fire incident was conducted. The silo structure collapsed towards the north side of pad. Fire department trucks sprayed large amount of water to the debris from the north side of the pad. Heavy demolishing equipment was later deployed at the north side of the pad to remove the debris offsite.

The results of impulse response test indicated relatively consistent mean mobility values throughout the pad. See Figure 3a. This indicated that delamination did not present near top surface of the concrete pad. Based on the results of UET, crack did not extend beyond 3 feet from the edge of concrete pad. See Figure 3b. Lab petrographic examination of concrete did not show signs of fire related damage. Thus, the cracks observed on the north side of pad were not attributed to fire. Signs of soil watered out from below the pad likely due to the fire extinguishing activities indicated that improper loading from the heavy demolishing equipment and lack of support of pad were the main contributing factors of the observed concrete cracks.

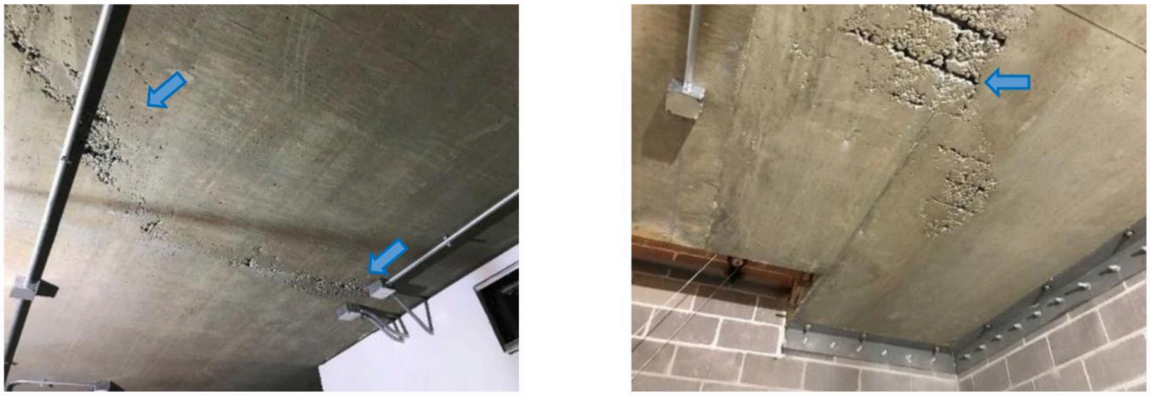


a. Mean mobility plot

b. UET model showing locations of crack

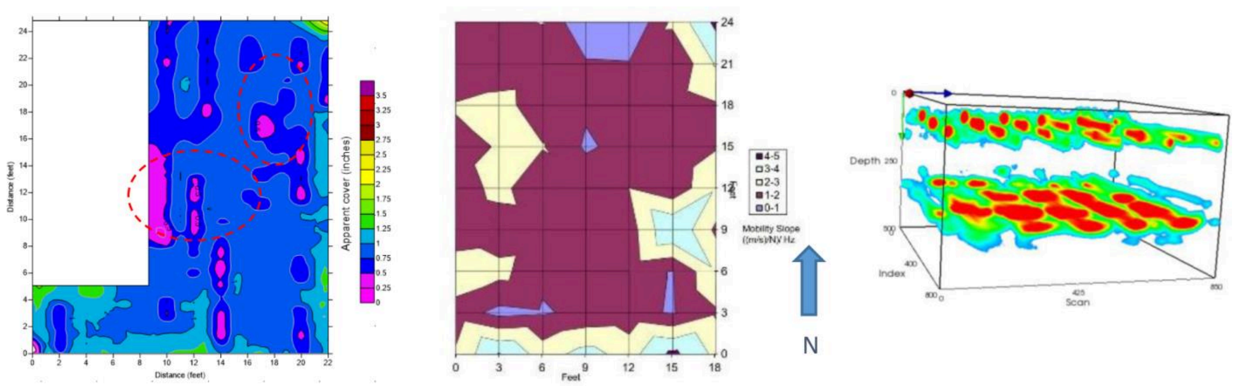
Figure 3 Typical distresses and test results on concrete foundation pad

Concrete Floor Slab of a Storm Refugee Building. A two-story storm refugee building attached to a food market was under construction in the state of Oklahoma. Surface voids and honeycombing were observed at the underside of a second-floor reinforced concrete floor slab after the formwork was removed. See Figure 4 below. The slab was 300-mm (1-foot) thick and reinforced with two mats of steel rebars at a center-to-center spacing of 150-mm (6-inch). The specified concrete cover of the top and bottom mat of rebars was 19-mm (0.75-inch), with an acceptable range which was from 13-mm (0.5-inch) to 32-mm (1.25-inch). To determine the contributing factors and the extent of the anomalies, ground penetrating radar (GPR) survey, impulse response test, and ultrasonic echo tomography exploration were utilized for evaluation.



a. Surface honeycombing near west wall b. Surface honeycombing near east wall

Figure 4 Surface honeycombing observed at underside of second floor slab (Images by Zhengqi Li)



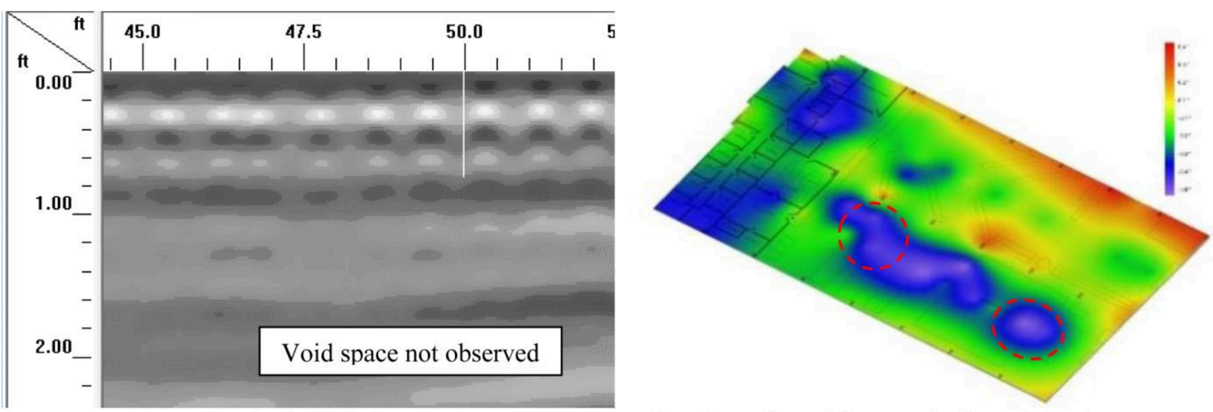
a. Concrete cover of bottom mat (GPR) b. Mean mobility plot c. Typical UET 3-D image of concrete

Figure 5 Results of NDE performed to reinforced concrete floor slab

A GPR with a 1600 MHz antenna was used to detect the locations of rebars and the concrete cover in the slab. It was observed that the concrete cover of the top mat rebars was generally more than the specified cover. The concrete cover of the bottom mat rebars was generally less than the specified cover. The locations of surface honeycombing observed at the underside of the slab were at the locations where the concrete cover was less than 13 mm (0.5 inches). See red circles in Figure 5a below for approximate locations of concrete surface honeycombing.

The impulse response test was performed on the top surface of the floor slab in accordance with ASTM C1740. The results of average mobility are presented in Figure 5b. A relatively high average mobility may indicate possible anomalies in the slab (ASTM C1740 2016). In this case, most of the average mobility was from 1 to 2. There was one localized area that had exhibited a relatively high average mobility value of about 4. Although average mobility value of about 4 was not a strong sign of internal anomaly, UET tests were performed on the top side of the slab to further investigate the condition of the slab at this location and at locations above honeycombing. Based on the UET results, the only sources of reflections were rebars and underside of the slab. Internal honeycombing and voids were not observed. See Figure 5c. The small concrete cover of the bottom mat of rebars has resulted in difficulties in consolidating the concrete and has contributed to the visually observed surface honeycombing. It was determined from UET survey that the surface honeycombing was limited below the bottom mat of rebars.

Figure 6 Circular crack on concrete slab (Image by Zhengqi Li)



a. Typical GPR images b. Results of floor relative elevation survey

Figure 7 Results of NDE performed to slab-on-grade at warehouse

Concrete Slab-On-Grade Foundation of a Warehouse Building: Circular cracks were observed at two locations on a concrete slab-on-grade of a six-year-old warehouse building in the state of Texas. See Figure 6 below. The slab was 150-mm (6-inch) thick and reinforced with a single mat of rebars at a center-to-center spacing of 250 mm (10 inches). The owner of the building was concerned with possible sinkholes under the slab and had requested a GPR survey to be performed. The author's team had recommended performing floor relative elevation survey as a preliminary assessment of the potential foundation movement in addition to the GPR survey.

Based on the GPR survey performed on the floor area of the warehouse, below slab sinkholes or voids were not observed. See a typical GPR image in Figure 7a. Floor relative elevation survey indicated that the floor elevations near the two circular cracks were lower than the other part of the building, and these two low floor areas were at the locations of frequent heavy forklift operation around storage selves. See circles in dash line in Figure 7b for approximate locations of circular cracks. In this case, overloading was considered to be a potential factor contributing to the settlement movement of the floor slab.

CONCLUDING REMARKS

Cracks in concrete occur when tensile stress exceeds the strength of concrete in tension. Cracks in concrete help us to trace the history of stress condition of concrete. A visual condition assessment, preferably involving crack mapping, of the slab system is recommended to be performed as a preliminary phase of the assessment. The assessment of concrete slab system using NDE techniques involves testing some properties of concrete and reinforcing steel. Some NDE methods are able to test a large area of concrete slab surface in a relatively short period of time, such as GPR and impulse-response test. Some NDE methods provides more detailed information of subsurface conditions, however, they are not suitable to test a large area of concrete slab surface within a reasonable period of time. It is recommended to first perform NDE that can rapidly screen slab areas to identify some localized areas for further destructive and non-destructive studies. Properly performed NDE help us to reduce the needs of destructive efforts, avoid blind destructive work, and save budget and time.

REFERENCES

ACI (American Concrete Institute) Committee 228. (2003). ACI 228.1 R-03, *In-Place Methods to Estimate Concrete Strength*. ACI. Farmington Hills, MI, USA.

ACI (American Concrete Institute) Committee 302 (2004). ACI 302.1R-15, *Guide for Concrete Floor and Slab Construction*, ACI. Farmington Hills, MI, USA.

ACI (American Concrete Institute) Committee 228. (2013). ACI 228.2 R-13, *Report on Nondestructive Test Methods for Evaluation of Concrete in Structures*. ACI. Farmington Hills, MI, USA.

ACSM (American Congress on Surveying and Mapping). (2005). *Definitions of Surveying and Associated Terms*. 2005 American Congress on Surveying and Mapping, Gaithersburg, MD, USA, pp 99-101.

ASTM (ASTM International). (2016). ASTM C1740-16, *Standard Practice for Evaluating the Condition of Concrete Plates Using the Impulse-Response Method*. West Conshohocken, PA, USA. https://doi.org/10.1520/C1740-16.

De La Haza, A.O., Samokrutov, A.A., and Samokrutov P.A. (2013). "Assessment of concrete structures using the Mira and Eyecon ultrasonic shear wave devices and the SAFT-C image reconstruction technique." *Construction and Building Materials*, Volume 38, pp. 1276-1291. https://doi.org/10.1016/j.conbuildmat.2011.06.002.

Li, Z. and Rangaraju P.R. (2015). "Effect of Sand Content on Properties of Self-Consolidating, High-Performance Cementitious Mortar." *Transportation Research Record: Journal of the Transportation Research Board*, Volume 2508, pp. 84–92. https://doi.org/10.3141/2508-11.

Li, Z. and Rangaraju P.R. (2016). "Development of UHPC Using Ternary Blends of Ultra-Fine Class F Fly Ash, Meta-kaolin and Portland Cement." *First International Interactive Symposium on Ultra-High Performance Concrete*. Des Moines, Iowa, USA, July 2016.

Li, Z. (2016). "Drying shrinkage prediction of paste containing meta-kaolin and ultrafine fly ash for developing ultra-high performance concrete." *Materials Today Communications*, Volume 6, pp. 74-80. https://doi.org/10.1016/j.mtcomm.2016.01.001.