ABSTRACT

Steel concrete steel (SC) is a structural typology and construction method. Continuous steel plates are used on the surfaces of concrete walls/slabs, having both the roles of formwork and tensile reinforcement. The steel plates completely replace the longitudinal reinforcement, but shear reinforcement may still be present. SC gained popularity in industrial applications, with the notable use in modules of the AP-1000 nuclear power plant (NPP).

The presence of thick continuous steel plates on both sides of the construction elements hinders the use of many traditional non-destructive evaluation (NDE) techniques to assess concrete quality or damage. In fact, reliable and cost effective assessment of structures is an outstanding challenge to the use of SC construction in nuclear applications.

To understand the limitations and possibilities of NDE techniques, several tests were performed on full scale SC elements. The elements were approximately 0.8x0.8x9.0m beams, tested earlier to static loads and with understood damage of the concrete. The NDE methodologies applied were Ultrasound 3D tomographer, Impact-Echo, Impulse-Response, Ground Penetrating Radar, Betatron and Ultrasonic testing. The objective was to detect cracks of different sizes and configurations in the beams. Width ranges of 0.1…1 mm were studied, on cracks perpendicular or oblique to the surface, generated by pure bending and combined bending and shear. Both crack types may be present in NPP walls/floors damaged by accidental overload.

The results show that Ultrasound 3D tomographer (as well as the other ultrasonic testing devices) and Ground Penetrating Radar are not suitable for testing through the steel surface, due to loss of the transmitted energy in the steel plates. Impact-Echo testing revealed promising results whereas Impulse-Response is suitable for detecting de-bonding of the steel plate from the concrete. Radiographic testing proved to be applicable in cases when the cracks had sufficient opening and length close enough to the film side.

INTRODUCTION

SC technology is employed in the nuclear field in several elements of the AP1000 plant design. The SC elements have been introduced in key buildings, as a means to achieve higher levels of prefabrication and economy. The SC modules received approval from NRC as part of the AP1000 design after a few rounds of review (Boyd, 2010). Containment internal structures, structures inside the containment vessel which supports the reactor coolant system, piping systems and related equipment are mostly planned from SC modules. Walls above a certain elevation are constructed from SC modules, which are pre-fabricated and lifted as a whole to final position. The steel module is then concreted in-situ (Westinghouse, 2011). The auxiliary building has in its center an SC module used for the cell structure of the spent fuel pool, cask loading pit, etc. The reactors are under consideration to be built in Europe.

While units of AP1000 are not planed in Finland, recent regulations (YVL E.6, 2013) allow the use of modular composite structures in Finland (Välikangas, 2015). Since steel plates create a continuous shield around the concrete, questions have been raised concerning the available methods to inspect concreting quality, long-term performance or post-accident integrity of the SC elements, in different phases of the review process.

In the Generic Design Assessment (GDA) phase of by the UK’s Office for Nuclear Regulations (ONR), it was found that the reactor typology is suitable for construction in the UK. The question of operational inspection and maintenance of civil structures, including SC, were not considered in detail in the GDA report. However, GDA assessment identifies manufacturing
inspections as an issue (ONR, 2011a, ONR, 2011b). The US Nuclear Regulatory Commission (NRC) conducted reviews and certification of AP1000 (NRC, 2004, NRC, 2005, NRC, 2011). The NRC raised questions concerning the construction and inspection methods planned for the inspection of voids, cracking, delaminating, and substandard construction of concrete. The assessment asked for selection of the NDE methodologies suitable for the qualification and inspection program. In the context of the review, NDE test have been performed on SC modules. However, reliable and cost effective ND testing of SC is an open issue.

As an example, WestDyne carried out ND evaluations using simulated voids in SC mock-ups of different sizes (Clayton and Smith, 2013). Ultrasonic and impulse-echo techniques were tried on the specimens. For one specimen the physical dimensions proved to be limiting the tests performed, but simulated concreting voids could be detected in the larger specimen. It was reported that delamination between the steel plate and the concrete core made inspections impossible in certain locations. Delamination is identified as a potential limiting factors for applying NDE for SC walls (Clayton and Smith, 2013).

**SC elements for this study**

SC elements comprise of two steel plates with concrete infill. Welded studs and tie bars ensure shear transfer between steel and concrete (Figure 1.a). The specimens were damaged during static tests aimed to study bending and shear behavior (Figure 1.b). NDE measurements were performed after load-testing with concrete having different curing periods (Tuhti et al., 2016, Rapaport, 2016).

Maximum aggregate size for the concrete used in the SC elements was 16 mm. The concrete was a self-compacting C30/37 with high workability, comparable to normal pavement/flooring concretes used in Finland. No information was available on the density of the concrete at the time of the NDE measurements, but the estimation was that it can be taken 2400 kg/m³. The velocity for longitudinal wave propagation in concrete was assumed to be between 3200 and 4400 m/s, as commonly reported in literature (Aggelis et al., 2011, Chai et al., 2011, IAEA, 2002). The concrete material can be assumed to be homogeneous, in the undamaged regions.

![Figure 1](image1.png)  
**Figure 1** – (a) The steel formwork of SC and (b) load-test arrangement in the static test, with steel plates top and bottom (Koukkari and Fülöp, 2013).

Detailed measurements were available for the specimens from the mechanical (i.e. static) test phase together with FEM model results. During the static tests the concrete was cracked in a controlled way, with two types of cracks present. The bending specimens had several cracks perpendicular to manner steel plate forming the faces of the beams, and penetrating deep across the beam (Figure 2.a). Depending on the location, these cracks had a width of 0.1…2.5 mm and could run as deep as 80% of the height of the beams. They were visible on both sides of the beams and can be assumed to cross the entire width. The second were cracks formed in regions with high shear (Figure 2.b). These cracks were oblique to the surface steel plates, starting with an angle of about 45 degress. Shear cracks were also visible on both sides of the beams, and a range of widths were available.

Both crack types offered unique opportunities to study NDE methods. The bending cracks not only create a discontinuity at the steel concrete interface, but also offer a deep void perpendicular to
the face of the beams. On the other hand, shear cracks provide a reflection surface within the concrete at an almost constant angle, offering detection opportunity with other NDE techniques.

The goal of the NDE study was to evaluate the possible inspection methods for testing the integrity of the SC elements. The methods evaluated in this study were: ultrasonic measurements using pulse echo technique; radiographic inspection, using a 7.5MeV Betatron as x-ray source; ultrasound 3D tomographer (MIRA); Impact-Echo (DOCter); Impulse-Response (s′MASH); Ground Penetrating Radar (Handy Search NJJ-105).

NDE METHODS AND MEASUREMENTS

Ultrasonic testing

Ultrasonic testing was performed by using pulse-echo technique and wet coupling, with Krautkrämer USM 35. In one type of measurement the goal was to investigate if a fraction of an ultrasonic beam would shift from steel to the concrete, through steel-concrete interface. The estimation was that, if the sound beam would shift from steel to concrete in tightly attached regions, the back wall echo would be 3dB lower compared to a situation where the steel plate was detached from the concrete. In the second type of measurements, Ø6.5 mm side-drilled holes were used as reflectors to investigate if it was possible to detect them by pulse-echo technique and gel coupling. No statistically significant difference was observed between steel-air interfaces and steel-concrete interfaces in the first type of measurements, meaning that almost 100% of the sound wave was reflected back from the steel-concrete interface. The pre-drilled “reflector holes” could also not be detected. Hence, the ultrasonic method was not effective for the examining SC structures.

Radiographic testing using Betatron MIB 7.5 accelerator

The betatron is a small-size cycle model accelerator with a pulse supply and a focal spot of approximately 0.3x3 mm. X-raying is performed with the constant nominal 7.5 MeV peak energy. The equipment is designed for NDE and particularly for diagnostics of building constructions.

Bending cracks were x-rayed so that the radiator unit was attached directly against the SC beam face, so that the presumed cracks would be x-rayed along the longest possible crack dimension with the x-ray beam aligned with the cracks. The film plates were attached directly to the opposite side on the surface of the beam. The x-raying was performed using digital film plates of two different resolution/exposure rate, meaning a faster but slightly less accurate film (“10% film”) and a slower but slightly more accurate film (“30% film). Source-to-film distance (SFD) was approximately 1000mm, including roughly 200 mm distance from focal spot to the radiator unit’s front face. Exposure time was 600s for the 10% film and 1800s for the 30% film type.

The radiograph for Crack 3 (Figure 3.a), which was on the detection limit, is given in Figure 3.b. The main crack, but also other cracks were visible. Based on four tests it was concluded that the x-raying technique was efficient to detect cracks behind the steel plates down to the width of 1mm.
Figure 3 – (a) Image of Crack 3 from the lateral side of the beam, the green line representing the position of the film; and (b) two tie bars (light) and several cracks (dark) visible in the 10% digital film with exposure 600 s

**Ultrasound 3D tomographer (MIRA, Germann Instruments)**

The MIRA creates a three-dimensional representation (tomogram) of internal defects that may be present in a concrete object. The detection is done almost in real time and in situ. MIRA is based on the ultrasonic Echo method using transmitting and receiving transducers in a "Pitch-Catch" configuration. The MIRA antenna uses an antenna composed of an array of 40 dry point contact (DPC) transducers, which emit shear waves (S-waves) into the concrete.

Testing by the MIRA system was performed on the steel surface of the girder along 1 meter of the girder upper part. In the MIRA case, the steel plate causes extremely intense wave reflections and wave energy loss, followed by repeating “phantom” reflections. No clear indication regarding the internal object condition could be given. According to the results it was concluded that the Ultrasound 3D tomographer is not suitable for testing on steel surface.

**Impact-Echo (DOCter, Germann Instruments)**

The impact-echo method is based on monitoring the periodic arrival of reflected stress waves (P-waves) and is able to obtain information on depth of an internal reflecting interface or the thickness of a solid member. A short-duration (<100 µs) stress pulse is introduced into the member by mechanical impact. High fidelity displacement transducers are used to measure the surface displacement due to an impact. The time-displacement response is converted to a frequency response, using a fast Fourier transform algorithm. The dominant frequency peaks which are induced due to reflecting interfaces are analyzed in frequency domain. Impact Echo testing requires access to one surface of the test object.

Impact-Echo testing was performed on the steel surface of the beam in several test points, at intact and areas damaged by shear cracks. The idea was to compare the dominant frequencies to the anticipated theoretical frequency calculations, and to estimate if irregular testing results are detected in the damaged parts of the beams.

The impact-Echo system detects reflections of pressure waves. The pressure wave velocity should be obtained in order to perform the testing. The pressure wave velocity in the steel plates was taken 5900m/s (normal for steel). The pressure wave velocity in the concrete was calculated from the MIRA testing to be $C_p = 3454 \text{m/s}$. The theoretical thickness frequency of the pressure wave reflection of the solid steel plated girder was estimated to 2.12kHz. The detected thickness frequency of the solid undamaged beam was 2.44kHz, which to some extent differs from the theoretical thickness frequency, yet not substantially. Testing was performed by using 8 mm impactor (contact time $t=35 \mu\text{s}$) and 12 mm (contact time $t=55 \mu\text{s}$).

Further tests were carried out at location with oblique (shear) cracks at 565mm and 650mm from the steel surface. The theoretical frequency was 3.01kHz and 2.62kHz for these locations, while the detected thickness frequency was 2.93kHz and 2.44kHz respectively. The tests were performed by using 12 mm impactor.
According to the results it was estimated that there is a possibility that the Impact-Echo testing technique could be suitable for integrity evaluations of SC elements. Detected wave reflections i.e. dominant frequency peaks in damaged locations are clearly different in comparison to these in intact structure. The results seem promising and further validations should be performed.

**Impulse-Response (s’MASH, Germann Instruments)**

The Impulse-Response (IR) s’MASH test system is suitable for quick NDE screening of a plate-like structures aiming to evaluate the structure integrity and to identify suspicious areas for subsequent detailed analysis. The IR s’MASH system uses a low-strain impact, produced by a load cell instrumented hard rubber tipped hammer, to send stress waves through the tested element. The impact causes the element to vibrate in a bending mode and a velocity transducer, placed adjacent to the impact point, measures the resulting motion of the test element.

The time histories of the hammer force and the measured response velocity are transformed into the frequency domain using the fast Fourier transform (FFT) algorithm. The resultant velocity spectrum is divided by the force spectrum, to obtain the mobility as a function of frequency. The s’MASH calculates the mobility spectrum which is analyzed to obtain parameters representing the element’s respond to the impact. The most important monitored parameter is the Average Mobility [(m/s)/N)] which is the average of the mobility values from the frequency domain in range of 100-800 Hz. The screening by the IR system is done in a grid form. Test influence depth up to 0.3-0.5m from test surface, depending upon the tested object. The Impulse-Response s’MASH system was used for testing the steel surface in relatively intact areas at the girder mid area and clearly damaged areas, especially at the girder upper part (Figure 4).

![Figure 4 – IR test Zone 1, with the corner points marked. The scanned region included a large zone damaged by the crack (a). Average mobility in Zone 1, from 100 (purple) to 10 (green/grey) (b).](image)

The idea was to identify suspicious locations where the steel plate might be de-bonded from its concrete substrate. In locations where the steel plate is not bonded to the concrete, the lack of base support should cause high dynamic response in comparison to bonded locations. At these locations a high Average Mobility values were expected. Test Zone 1 is shown in Figure 4.a. In this zone 30 tests were performed in grid of 200mm x 200mm, with the results summarized graphically in Figure 4.b. One can clearly identify the high mobility areas (purple color), and the regions with relatively un-damages bond between the steel and concrete (grey and green color). It is clear that the IR method is suitable for detecting de-bonding of a steel plate from its concrete base.

**Radar Ground Penetrating Radar (Handy Search NJJ-105, Japan Radio)**

The Handy Search GPR is a small size instrument for carrying out surveys to locate reinforcing steel, metallic tendon ducts; measuring concrete cover over reinforcement and other embedment, measuring the thickness of slabs, detecting internal voids and deterioration or detecting embedded cables carrying electrical current. GPR is analogous to the ultrasonic pulse-echo technique, except that pulses of electromagnetic waves are used instead of stress waves.
When reviewing GPR results it was clear that the steel plate cause intense wave reflections and wave energy loss almost immediately on the steel plate, followed by “phantom” reflections. No clear indication regarding the internal object condition could be given. It was concluded that the GPR testing technique is not suitable for testing on steel surfaces.

SUMMARY AND CONCLUSIONS

The aim of this study was to apply different state of the art NDE- techniques, which are designed for pure steel or reinforced concrete structures, on SC beams (similar to NPP containment wall structure), and estimating the suitability of those NDE- techniques to perform integrity evaluation of SC. The conclusions are as follows:

- No ultrasonic signal could be transmitted through the steel plates into the concrete by the techniques that were used. Moreover, applicability of pulse echo technique using only one transducer seems limited to the concrete itself. Other ultrasonic techniques could be tested.
- Radiographic testing is applicable when the cracks had sufficient opening (>1mm) and length (>400mm) close to the film side. Method best suited for detecting bending crack. With the betatron relatively small areas can be inspected at a time and the x-raying times are long.
- The Ultrasound 3D tomographer is not suitable for evaluating object integrity when testing is performed on the steel surface.
- The Impact-Echo is possibly suitable, with some limitations, for evaluating object integrity when testing is performed on steel surface.
- The Impulse-Response is clearly suitable for evaluating the bond of the steel plate to the concrete base. The GPR is not suitable for evaluating object integrity when testing is performed on the steel surface.

In order to validate the suitability of the Impact-Echo and Impulse-Response NDE techniques a carefully planned mock up (several if possible) is recommended to be manufactured. The mock up should contain artificial failures/damages of different types. Further NDE testing should be performed on the mock ups. In case validation is successful, procedures for testing are recommended to be established for applications in actual structures.

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