INVESTIGATIONS WITH REINFORCED CONCRETE TOMOGRAPHY

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ABSTRACT

The *reinforced concrete tomography* (RCT) is a non-destructive technique that uses gamma rays to obtain diameters and positions of all steel bars in structural sections, even in cases of congested reinforcement, with an accuracy of ± 1 and 5 mm, respectively. This is well beyond what is achievable with other current methods such as the Ground Penetrating Radar, Covermeter, Acoustic Emission or Ultrasound. In addition, because of its "photographic" quality RCT can be used to investigate steel corrosion and voids in reinforced concrete. This methodology has been successfully used in hundreds of structures including bridges, buildings, bank treasuries, industrial establishments, silos and monuments. In this paper results obtained from a few cases of special interest are presented: 1) the investigation of defective grouting in ducts of a post-tensioned beam in Argentina´s largest bridge; 2) the study of underwater pillar sections at Ushuaia harbor; 3) the detection of termite-produced cavities in a hidden wood structure of a XVII century chapel; and 4) recent tests for the detection of corrosion in hinge deck bridges found in hundreds of locations on the UK trunk road and motorway network.

INTRODUCTION

Gamma rays have been employed to study the condition of concrete structures for more than five decades (Mullins et al., 1949; British Standard, 1986; McCann and Forde, 2001). The extension of this application for locating steel reinforcing bars was proposed shortly after the first reports on the use of gamma rays in this field were published (Whiffin, 1954; Forrester, 1957).

However, probably owing to the requirement of licenses and the current social apprehension towards radiation, the interest for this particular NDT tool for civil engineering has until now been limited and has not been developed to its full potential (McCann and Forde, 2001; Malhotra, 1976).

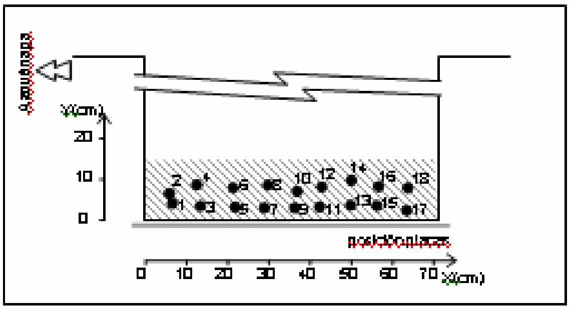

Fig. 1. RCT results for a beam 70 cm wide obtained with a ^{192}Ir source.

THASA, a company founded in 1992 by personnel with a physics background, has focused on the improvement of this technology both technically and economically. By exploiting the computational resources that are available nowadays and by developing processes that use low energy sources, i.e. minimizing disturbance to the public, it has been possible to attain a practical low cost method that provides essential information for the verification of the load capacity of a structure with a precision not attainable with any other technique in use today (Fig. 1). In addition, this method can be employed for the identification of corrosion as well as honeycombing and voids in concrete because the technique allows “looking” inside structures with photographic fidelity (Fig. 2).

The method, called RCT (i.e. Reinforced Concrete Tomography) has been applied to study the condition of hundreds of concrete structures such as bridges, post-tensioned ducts, buildings, bank treasuries, docks, monuments, etc. (Frigerio et al., 2004; Mariscotti et al., 2006)

In this paper results obtained in four cases considered to be of special interest, because they do not represent the mainstream RCT applications, are presented. These cases are: 1) the investigation of defective grouting in ducts of a post-tensioned beam in Argentina´s largest bridge; 2) the study of underwater pillar sections at Ushuaia harbor; 3) the detection of termite-produced cavities in a hidden wood structure of a XVII century chapel where a non destructive approach was of importance; and 4) recent tests for the detection of corrosion in hinge deck bridges found in hundreds of locations on the UK trunk road and motorway network

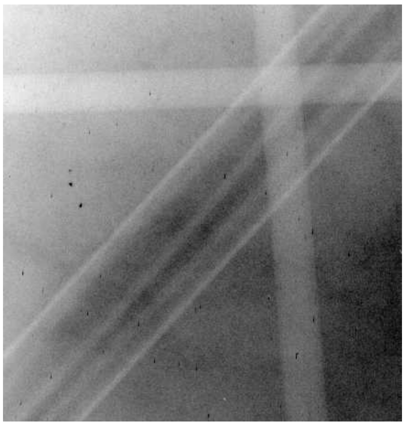

Fig. 2 Details of an electrical conduit in a slab with cables inside illustrate the sensitivity achievable with RCT.

BRIEF DESCRIPTION OF THE RCT METHOD

The RCT method is similar to computed tomography used in medicine except that gamma rays are used instead of X-rays and that it is not necessary to have access to the object of study from a large range of angles.

Gamma rays have the advantage over X-rays that they are emitted spontaneously so that electrical power is not needed. In addition, their wavelength is more appropriate for use in investigating concrete elements, as these are significantly denser than the human body.

Furthermore THASA has developed ways (Mariscotti et al., 2007) to study large sections of concrete structures with a relatively small source of ^{192}Ir (Fig. 1). This provides a portable system, which is easy to carry and handle and facilitates the fulfillment of safety requirements.

Fig. 3. Zarate-Brazo Largo bridge complex in the limit between Buenos Aires and Entre Ríos.

Both conventional and digital CR 35 x 43 cm (14” x17”) plates or, in special cases, gamma-ray spectrometers, are used to register the intensity of the radiation transmitted through the concrete section under study. The 3D reconstruction of the reinforcement (see e.g. Fig.1) is achieved by applying multiple exposures or by employing the penumbra method (Mariscotti et al., 1998) and by using specially designed hardware, to obtain the “field” data, as well as software to analyze them (Mariscotti et al., 2007).

When gamma rays travel through matter, scattered radiation is generated that falls onto the plate and blurs the contrast reducing the image quality. In the case of concrete, as opposed to the human body, this phenomenon is rather severe due to the higher density, especially when the “internal source mode” is used. The development of the Montecarlo-type GAMMASIM program (Thieberger et al., 2006) made it possible to determine optimum filters to mitigate this problem. On the other hand, the special application of gamma-ray spectrometers as substitute of films has the important advantage that it is possible to electronically filter out the unwanted scattered radiation almost completely.

CASE 1. DETECTION OF VOIDS IN DUCTS OF POST-TENSIONED BEAMS.

A particularly important application of RCT is the investigation of faulty grouting in ducts of large post-tensioned beams. This type of work (THASA, 1999) was carried out in Argentina's largest bridge complex, Zárate-Brazo Largo, which joins the provinces of Buenos Aires and Entre Ríos (Fig. 3). The general condition of the cables and, in some cases, of the wires, was also evaluated, rebars/stirrups were observed and the existence of honeycombing was determined.

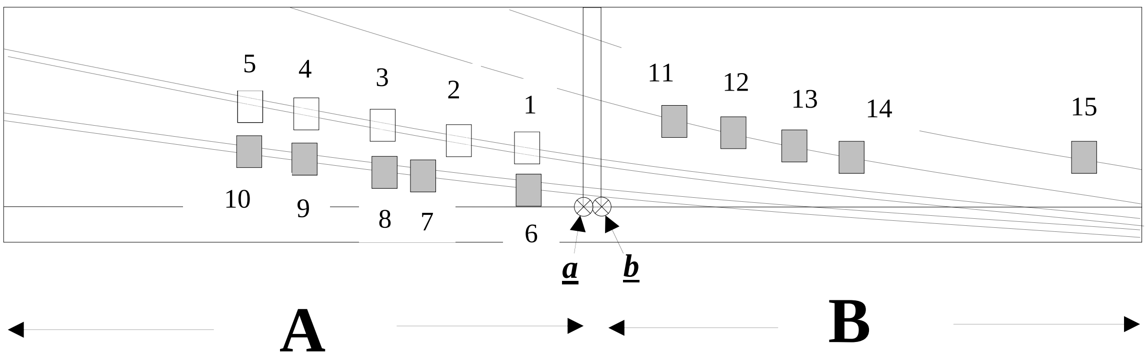

Fig. 4. The dotted lines indicate the ducts and the rectangles show the (approximate) positions of the plates obtained in these measurements. Source-plate arrangement in 1 to 5 was opposite to that in 6 to 15.

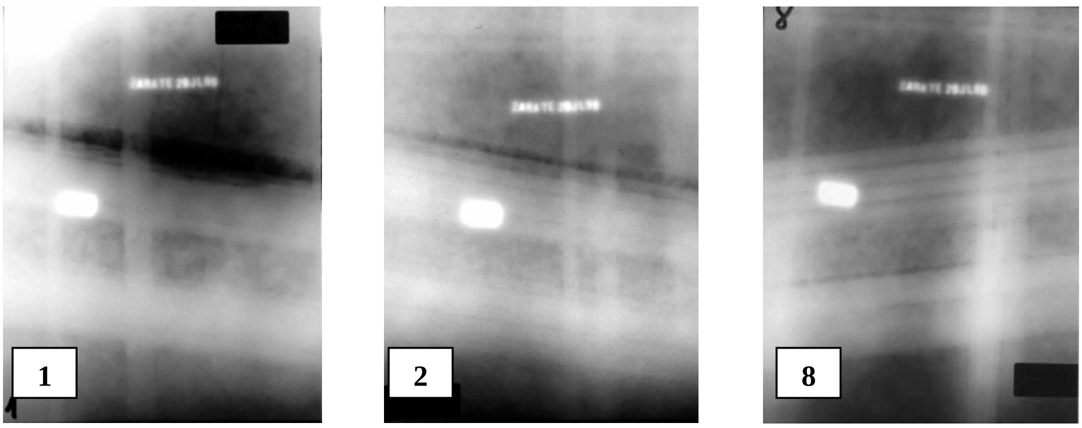

Fig. 5. Gammagraphies at locations 1, 2 and 8 in Fig. 4. Plate No. 1 shows a marked void in the upper duct for lack of grouting (dark band). This defect diminishes toward the left in Fig. 4 and is barely visible in Plate No. 2. Plate No. 8 does not show any sign of defect in the grouting. This gammagraphy also shows that the condition of the individual wires is good.

In total 15 locations, shown in Fig. 4, corresponding to 4 different ducts were studied with a 93 Ci ^{192}Ir source. At location 1 a severe void was found (Fig. 5 (1)) on the upper part of the upper duct (seen as a black thick line). This fault is seen to diminish toward the left in Fig. 4 and is barely seen in plate 2 (Fig. 5 (2)) as a thin black line on the upper part of the upper duct. In the other locations the gammagraphies revealed no defects as can be seen in plate 8 (Fig. 5 (8)). The quality of the latter is good enough to allow assessment of the individual wires, which in this case do no exhibit any corrosion.

Another case of faulty grouting was observed in position 13 (Fig. 4) and plate 3 revealed honeycombing in the concrete matrix, below the ducts. This work also provided data on the number, position, diameter and condition of 12 mm stirrups (seen in Fig. 5 as vertical white bands).

CASE 2. UNDERWATER INVESTIGATION OF DOCK PILLARS AFTER A SHIP COLLISION.

This work was carried out at the *Dolphin* in the harbor of Ushuaia the southernmost city in the world and capital of the Argentine province Tierra del Fuego (Fig. 6).

This structure had sustained the collision of a big ship against its South East corner. Thus, after this event THASA was commissioned to undertake an investigation on the condition of the pillars (possible cracks and damaged reinforcement) both at sea level and near the seabed.

A team of divers was subcontracted and the source system and plate systems were housed in appropriate especially designed watertight containers. The deepest location was at 12 m under the sea level.

Fig. 6. A view of the Dolphin in Ushuaia harbor.

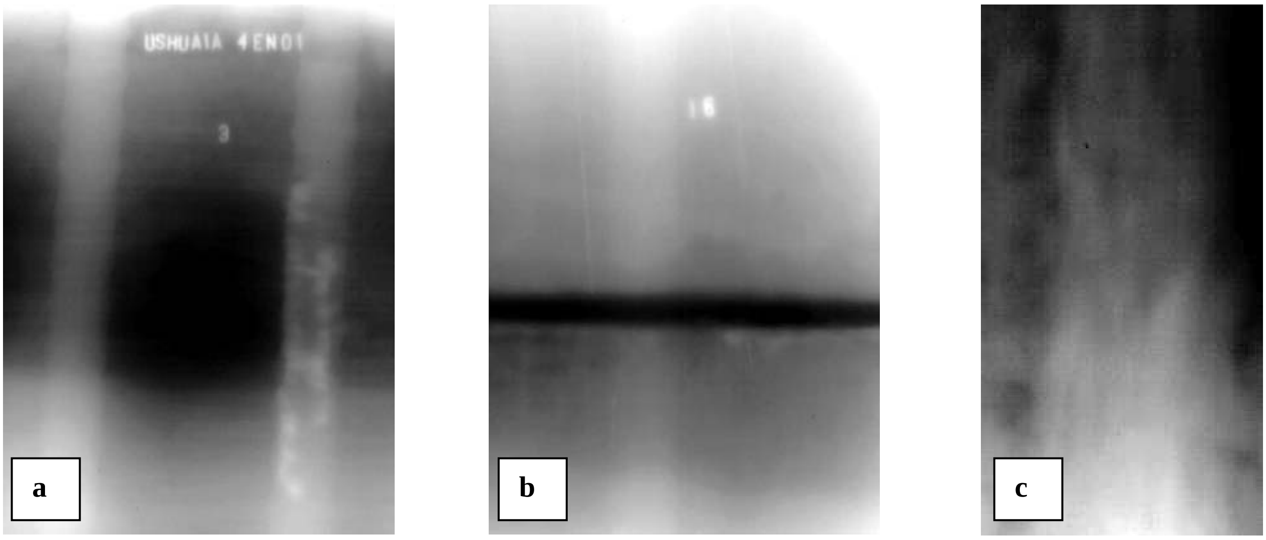

Fig. 7. a) A plate obtained at sea level showing two 32 mm rebars. The one on the right is damaged with incrustations and corrosion; b) A plate obtained at about 30 cm above the seabed, showing a crack in the steel sleeve; c) Case of corrosion with part of the bar vanished.

These pillars have a steel sleeve. Because of their diameter (80 cm) holes were drilled at angles with a pneumatic drill, so that the Ir source could be introduced inside the pillar to irradiate a flexible plate held against the pillar surface at about 25 cm from the source. A sequence of irradiations was performed in each sector spaced vertically 15 cm from each other in order to have a better check on the continuity of the rebars.

In this work systematic cracks in the steel sleeves of the pillars at about 30 cm above the seabed and several cases of corroded rebars were found (Fig. 7).

CASE 3. DETECTION OF CAVITIES IN A WOOD STRUCTURE.

Using RCT, an investigation was carried out at the wooden roof of a historical chapel built in the XVII century in Córdoba, Argentina. The chapel was recently designated part of Mankind Heritage by UNESCO (Cravenna et al., 2007).

Termite-produced fist-size cavities were found in the sheathing boards and beams under the tiles when, because of signs of moisture in the ceiling, tiles were removed in a small section near the front left corner of the roof.

Fig. 8 is a photo of the ceiling of this chapel and Fig. 9 shows one section of the structure of the roof. Sets of 3. 7 x 28 cm wood logs (locust tree), one straight and two curved, spaced at 65 cm centres, support sheathing boards and 6 layers of clay tiles. The darker areas in Fig. 9 correspond to a couple of cavities found in the wood structure.

Fig. 8. View of the ceiling of the chapel

A non-destructive technique was sought to check the condition of the rest of the roof. The possibility of using gamma rays from a ^{192}Ir source was not readily evident. This was because of the small density difference (which determines contrast) between the wood and the “object” of interest (essentially a hollow space with some termite residues) which in this case was estimated to be 0,5 g/cm^3. For this reason the GAMMASIM program was adapted to simulate the conditions of this case with the result that enough contrast would be obtained only for cavities larger than ~3 cm in the direction of the radiation.

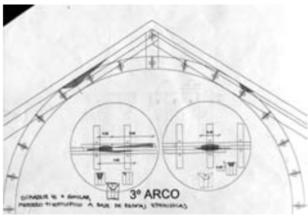

Fig. 9. Structure of the roof. Straight and curved beams support sheathing boards and tiles.

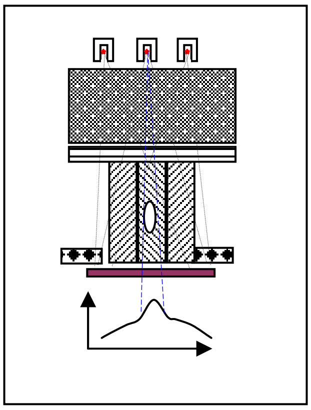

Fig. 10. Section view of the roof

Fig. 11. Sample of plate obtained in this work with source at the center.

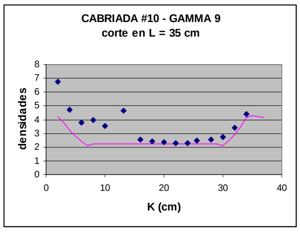

Fig. 12. Measured and calculated *D* distributions for a horizontal “cut” near the top in the gammagraphy of Fig. 10

Fig. 10 is a cross section view of the roof showing the 3 source positions (little squares at the top) used for examining each set. The upper area represents the tiles; below the tiles rest the sheathing boards and directly beneath are the beams. The thick brown line underneath the beams is the gammagraphic plate. The schematic plot at the bottom in Fig. 10 illustrates the expected intensity distribution along an axis on the plate if a cavity as that shown in the central log in Fig. 10 was present.

Fig. 11 shows one of the gammagraphies obtained during this work taken with the source at the center. The 3 adjacent logs are seen. The first and second from the left of Fig. 11 show some separation that gives rise to a black vertical line. The image of nuts, a white rectangle and a label are due to external references. A few XVII century nails (unexpected by the experts) are also seen. A careful calibration of photographic density *D* as a function of wood-equivalent thickness was obtained using the black areas, the nails and the reference elements for calibration.

A total of 10 sets were studied with 35 gammagraphies. Several one dimensional density (*D)* distributions were obtained for each gammagrahy and analyzed in plots like that in Fig. 12 that shows the measured and calculated values in blue dots and magenta line, respectively. The latter were obtained on the basis of the known configuration and estimated material densities (the wood density, was measured to be 0.7 g/cm^3) assuming no cavities or defects. Differences between the two sets of values signal a cavity (if the measured *D* is larger than calculated) or the presence of an element denser than wood (if the measured *D* is less than calculated).

The high point corresponding to the horizontal coordinate 13 cm in Fig. 12 corresponds to the black vertical line showing a small gap between the first and second log from the left in Fig. 11. The analysis shows that the depth of this gap is 15 ± 2 cm. The deviation between measured and calculated data towards the left of the plot in Fig. 12 corresponds to a lack of material *L* in the path of the gamma-rays equal to *L* = (5 ± 1) cm.

In this work, which may be the first of its type applying gamma-rays to examine non destructively the interior of wooden structures in monuments, it was found that 3 of the 10 sets investigated had voids of depths between 4 and 7 cm.

CASE 4. DETECTION OF DEFECTS IN HINGE DECK STRUCTURES

There are more than one hundred bridges in the UK on the trunk road and motorway network with concrete hinges (Fig. 13) in their decks. Scissor and dowel bars at the crossing point in the hinge are particularly vulnerable to corrosion in the event of bridge deck waterproofing failure. In this connection the UK Highways Agency (HA) has implemented a program to investigate various non destructive techniques to establish their ability to detect corrosion and for this purpose commissioned the Transport Research Laboratory (TRL) to construct (Badr et al., 2006) a full size mock-up of a hinge with embedded defects (Fig. 14).

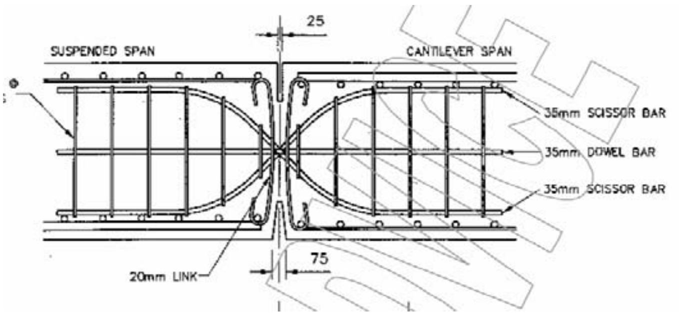

Fig. 13. Typical hinge detail showing the 2 scissor and 1 central dowel bars crossing at the center of the hinge.

In collaboration with Atkins (Vassou, 2005, SSR, 2006), THASA carried out measurements on this full-scale specimen (Fig. 14) to test whether RCT technology could effectively detect corrosion-like defects in the scissor and dowel bars at the center of the joint.

A ^{192}Ir source was provided by NDT Services Ltd who also assumed the responsibility for the radiological health and safety issues. Plates and a plate-reading instrument comprising a CR system were supplied by GE Inspection Technologies Ltd.


Fig. 14. View of the hinge specimen prepared by TRL

The specimen was 88 cm wide containing 3 sets of scissor and dowel bars with various hidden defects. As a first step the top of the specimen was swept with a covermeter to approximately locate these sets. On the basis of this information a first round of measurements with the source at the bottom and the plate on top were carried out. After analyzing these results a new set or irradiations was performed with adjusted parameters. In these series of experiments a specially designed box containing filters and reference elements was used in order to obtain precise positions, diameters and inclinations of the rebars. These data, together with simulations done with the GAMMASIM program and the identification of the rebar ridges, were essential in establishing the presence of defects. Several density *D* distributions (similar to those described in Case 3 above) were obtained for every one of the 9 rebars found in the specimen and compared among themselves and, in some cases, with the predictions of GAMMASIM. An example is

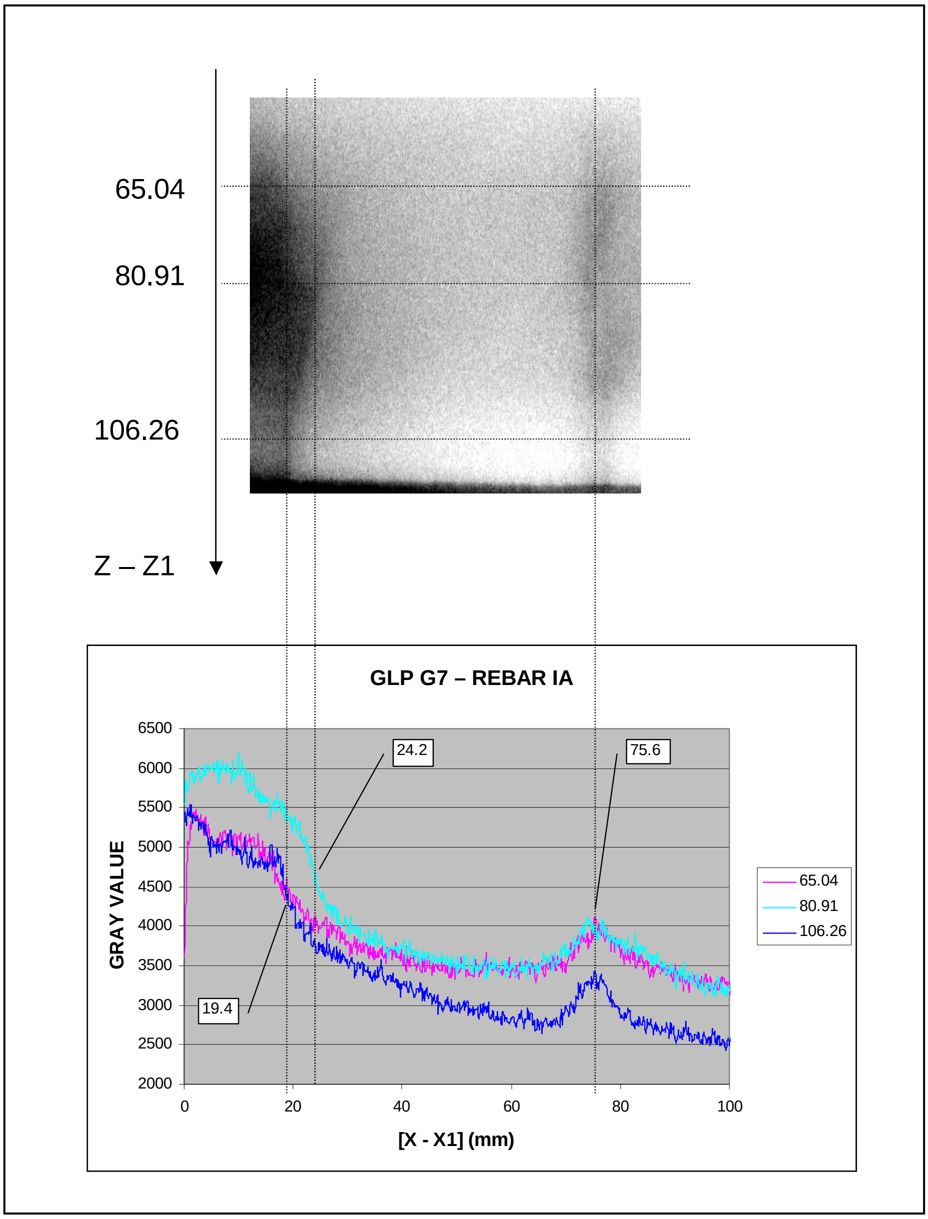

Fig. 15. Density *D* distributions for one of the scissor bars (IA#7). The light blue data points correspond to the notch seen on the left of the gammagraphy above. The difference at the point of maximum slope with the data in magenta and blue is 4.8 mm that corresponds to a notch size in the real bar of (2.4 +/- 0.2) mm.

shown in Fig. 15 where gray values (in this case equivalent to *D* photographic density values) in a gammagraphy are plotted as a function of position along an axis transversal to the rebar main axis Z, for 3 values of Z. The case shown here corresponds to one of the rebars where a notch is clearly visible (gammagraphy in the upper part). A precise determination of the size of this notch is obtained by comparing *D* distributions corresponding to different sections of the rebar. The light blue data points correspond to the section where the notch seen on the left of the gammagraphy above is largest. The difference at the point of maximum slope with the data in magenta and blue is 4.8 mm, which corresponds to a notch size in the real bar of (2.4 +/- 0.2) mm. In this work two notches like this one in a plane perpendicular to the radiation were well established. Determination of defects on a plane parallel to radiation is less straightforward. A lack of steel within a narrow radiation cone that passes through the center of the rebar will manifest itself as a "bump" in the center of the "valley-shaped" *D* distribution, such as those in Fig. 15. The amount of steel thickness equivalent that such a bump represents can be determined with the use of GAMMASIM. However, in this case more than one exposure is necessary to establish whether such a bump is due to corrosion in the steel or to a small void in the concrete material anywhere between source and plate within the radiation cone.

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CONCLUSIONS

The introduction of RCT has made it possible to study concrete reinforcements with unprecedented detail and accuracy. The four applications described here fall outside the scope of the routine inspections of reinforced concrete beams columns and slabs. Through these cases the limits of this technology were explored enabling knowledge expansion with regards to its capabilities and limitations. The cases presented in this paper relate mainly to voids and corrosion. The first one presents conclusive results on defective grouting in ducts of post-tensioned beams; in the second example the identification of cracks in the steel cover of underwater pillars and the detection of corrosion in the reinforcement at sea level are discussed; the third case deals with the detection of cavities in hidden wood structures, a hitherto unforeseen application of RCT but useful for historical monuments; and finally, the successful application of RCT for the detection of corrosion in hinge decks found in many UK bridges.

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