J Mater Sci (2007) 42:3280–3285
DOI 10.1007/s10853-006-0731-2

LETTER

Damage characterization of concrete panels due to impact loading by motionless X-ray laminography

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Received: 29 June 2006 / Accepted: 28 July 2006 / Published online: 27 March 2007

Introduction

Concrete structures are often subjected to extreme dynamic loading conditions due to direct impact. Typical examples of these loading conditions include transportation structures subjected to vehicle crash impact, marine and offshore structures exposed to ice impact, protective structures subjected to projectile or aircraft impact and structures sustaining shock and impact loads during explosions or earthquakes. The assessment and extent of damage to the structure associated with these transient dynamic loading conditions is of paramount importance. Often there are external visual signs of damage after dynamic loading events, however, the extent of damage inside the structure and the determination of its integrity remains obscure. Therefore, one needs to resort to non-destructive evaluation (NDE) techniques not only to detect damage but also to assess the severity of damage. Unfortunately, high-resolution NDE methods to characterize damage in structural materials have been less successful when applied to concrete, partly due to its inhomogeneous micro- and macrostructure associated with heterogeneities at various length scales that create interferences, such as scattering, attenuation, reflection and diffraction.

This paper illustrates the feasibility of using motionless X-ray laminography to detect and characterize damage caused by dynamic loading events. Plain and fabric reinforced concrete panels are subjected to impact loading by a steel projectile of certain initial velocity. The fabric reinforced concrete panels consist of polypropylene fabric attached to the front and back panel. Whereas in plain concrete panels, the damage due to impact loading is clearly visible, in fabric reinforced concrete panels the damage is obscured by the presence of the fabric. Hence, motionless laminography based on reverse geometry X-ray radiography is applied to these fabric reinforced concrete panels to obtain information on the damage evolution through the thickness of the concrete panel.

The motionless X-ray laminography concept and its advantage over conventional laminography are briefly described, followed by discussions on the effect of impact loading on plain and fabric reinforced concrete panels.

Motionless laminography X-ray system

The Motionless Laminography X-ray (MLX)® system used to assess impact damage in concrete panels was developed by the Digiray Corp [1]. The advantages of MLX over conventional X-ray systems are its speed, high contrast and quality of images, reduced radiation, and portability. The 2D spatial resolution of the MLX method is less than 12 μm and the resolution in the third dimension is 8 mils.

Laminography is commonly used when objects cannot be irradiated from all directions due to lack of access. In conventional laminography the X-ray source and the detector are moved synchronously in opposite directions. In some newer set-ups the X-ray source and the detectors are stationary but the object moves. The major handicap of

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conventional laminography is the complicated system set-up, the critical alignment and the presence of moving parts. The moving parts cause blurring which lowers image quality and resolution.

The MLX system, on the other hand, is motionless. The need for moving parts and the need for critical alignment is eliminated by utilizing a different geometry of the detection system. MLX is based on reverse geometry X-ray (RGX)® radiography [2]. The difference between conventional X-ray radiography and RGX is schematically illustrated in Fig. 1. The reverse geometry shows the object close to the source instead of close to the detector as in conventional systems. The X-rays are produced by a scanning beam generated in a raster pattern using a magnetically deflected electron beam inside the X-ray tube. In RGX this large X-ray scanning system is combined with a small detector as shown in Fig. 1. Objects placed near the source scatter X-rays which then bypass the small detector. The direct beam is preferentially detected and results in an image which is not blurred by scattering.

In MLX, the single detector is replaced by an array of 64 small detectors, which are simultaneously exposed to X-rays as shown in Fig. 2. Each detector generates a sharp ''unblurred'' image at a different angle which is then digitized and stored in the computer. Then each image is shifted with respect to every other image and all are added together. This generates slices, giving a layer-by-layer view of the object. There are no moving parts to degrade the image resolution. In a single short X-ray exposure it captures 1,000 X-ray slices that are 1 pixel thick with 8 mils resolution. These slices can be displayed individually or in a consecutive layer-by-layer motion picture.

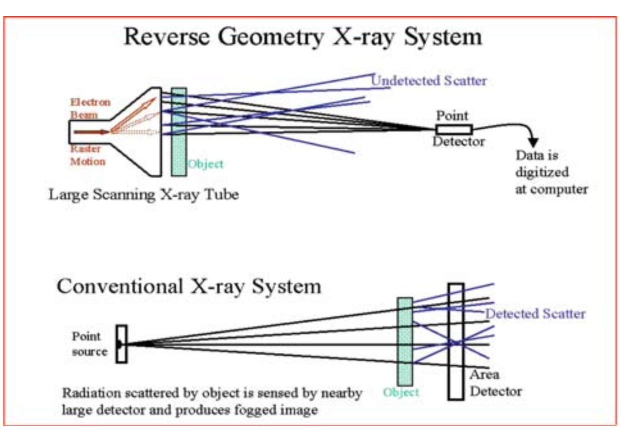


Fig. 1 Reverse geometry X-ray system versus conventional X-ray system

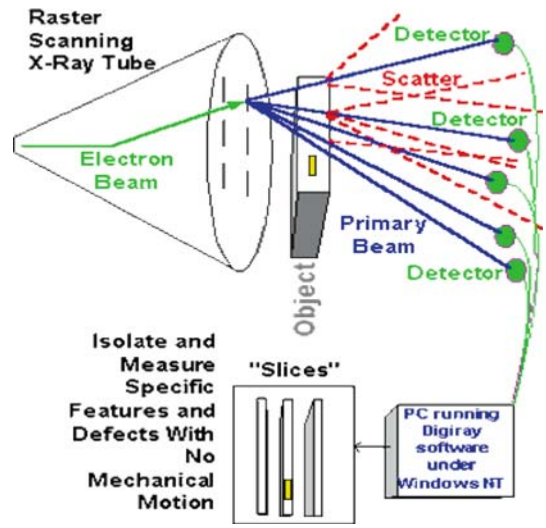


Fig. 2 In motionless X-ray laminography, the single detector is replaced by an array of small detectors, each being exposed to X-rays

Impact behavior of concrete panels

Impact loading causes damage to concrete structures [3–5]. One approach to reduce damage is to protect concrete with external elements. In a recent ongoing study [6] Polypropylene (PP) fabric was employed to investigate the effect of fabric on penetration and energy absorbing capacity of concrete. Impact tests were performed on square concrete panels (30.5 cm × 30.5 cm) with nominal thickness of 2.54 cm in the ballistic laboratory at UC Berkeley. All panels consist of normal strength concrete (i.e., compressive strength of 35 MPa). Impact tests were performed using a gas gun and sharp cylindrical projectiles of 34 g in weight, 1.27 cm in diameter, and 2.54 cm in length. The initial velocity of the bullet was 90 m/s. The test set-up and impact results are described in detail in ref. [6]. This paper focuses on the characterization of the damage.

Visual Inspection of damage in concrete panels

Figures 3 and 4 depict the damage induced on the front and back face of the plain and PP reinforced concrete panels. In plain concrete panels, spalling occurred from the front face (Fig. 3a). A deep crater formed on the back face (Fig. 3b) due to removal of concrete material. The crater formation was accompanied by debris flying off the back face at a speed of 8 m/s. The depth of the crater is 20 mm. The non-uniform size of the crater reflects the non-uniform micro- and macrostructure of concrete due to the size gradation of coarse and fine aggregates. Through-thickness radial cracks are also present and indicated by arrows in Fig. 3a and b. Figure 4 depicts the concrete panel protected by PP fabric

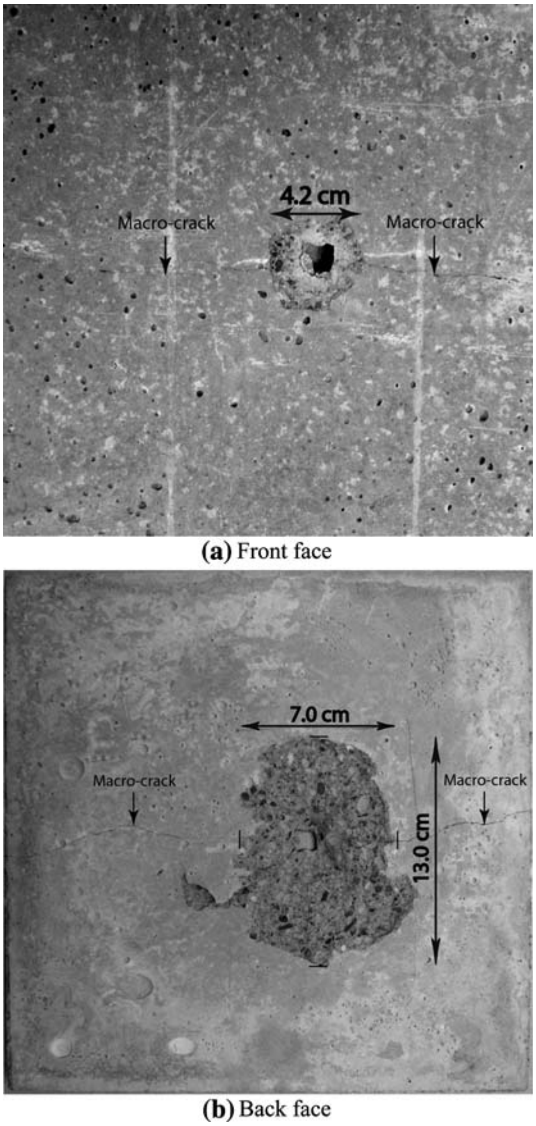


Fig. 3 Damage of front and back face in the plain concrete sample (PC)

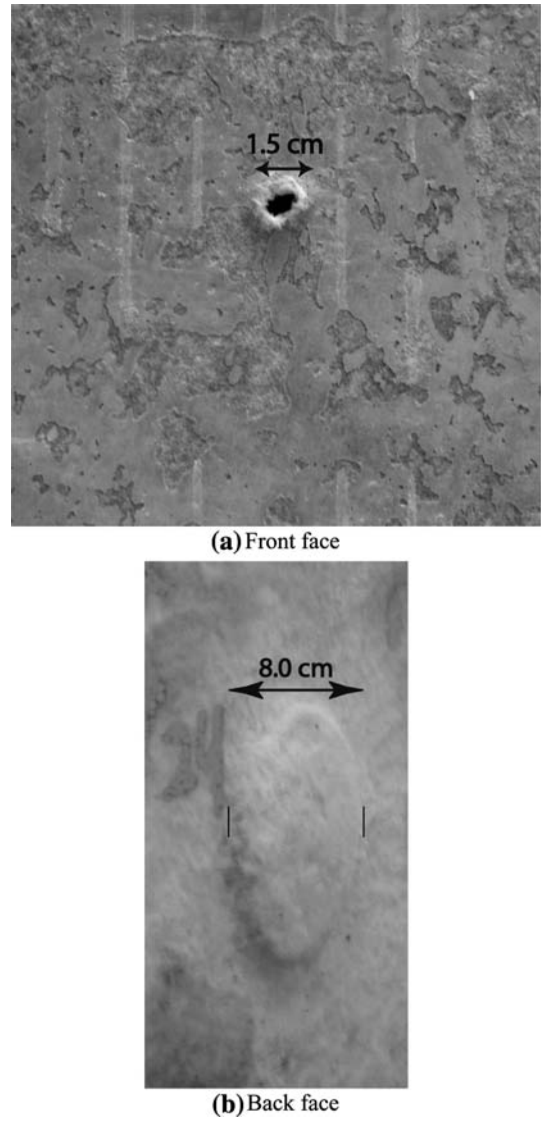


Fig. 4 Damage of front and back face in the sample protected by Polypropylene fabric (PP)

on both sides. The fabric prevented spalling from the front face hence the damaged region is smaller compared to the plain concrete panel. A bulge formed on the back face but the fabric remained intact and the bullet was stuck in the concrete panel. Since the damage to the concrete is obscured by the presence of the fabric the damage was analyzed by MLX as will be discussed below.

Damage detection with MLX

The MLX method provides the ability to look through the concrete panel layer by layer providing information on the extent of damage at different layers along the thickness of the concrete panel. Figure 5 depicts the evolution of damage in PP reinforced panels with images taken at different depths along the thickness of the panel. The first image (top left in Fig. 5) corresponds to the front surface of the panel (also shown in Fig. 4a). The last image (bottom right in Fig. 5) depicts the damage of the back face (also shown in Fig. 4b). All the images are 12.4 cm × 12.7 cm. Within each image the brightness varies according to the X-ray absorption. Dark regions correspond to low-density regions (e.g., cracks and defects) and light regions show the high-density phases. No through-thickness radial cracks developed in these concrete panels but various types of damage to the concrete can be discerned from Fig. 5. The almost spherically shaped black hole represents the removal of material caused by the penetrating projectile. The size of the black hole in the first image in Fig. 5 is equivalent to the dimension indicated in Fig. 4a. The

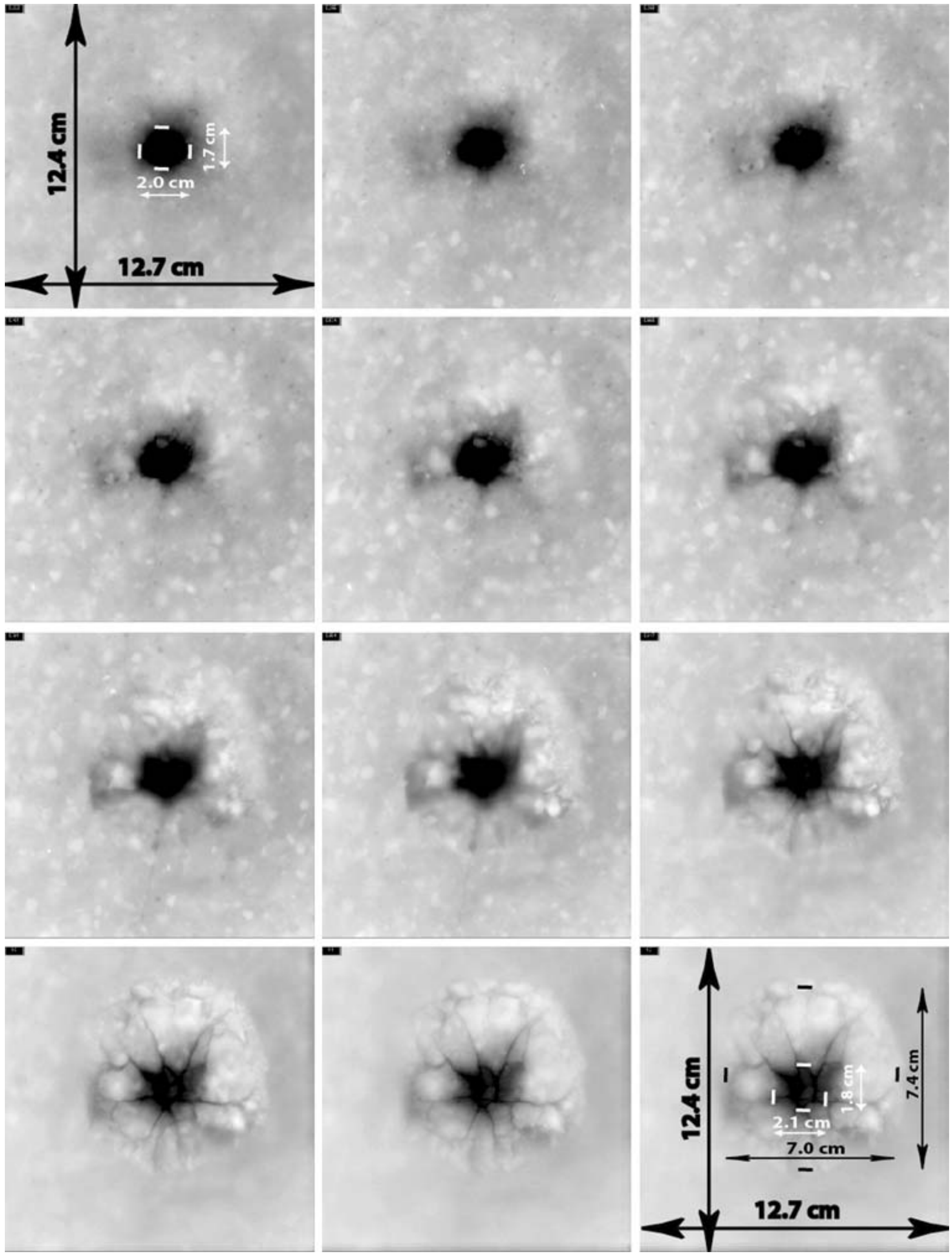
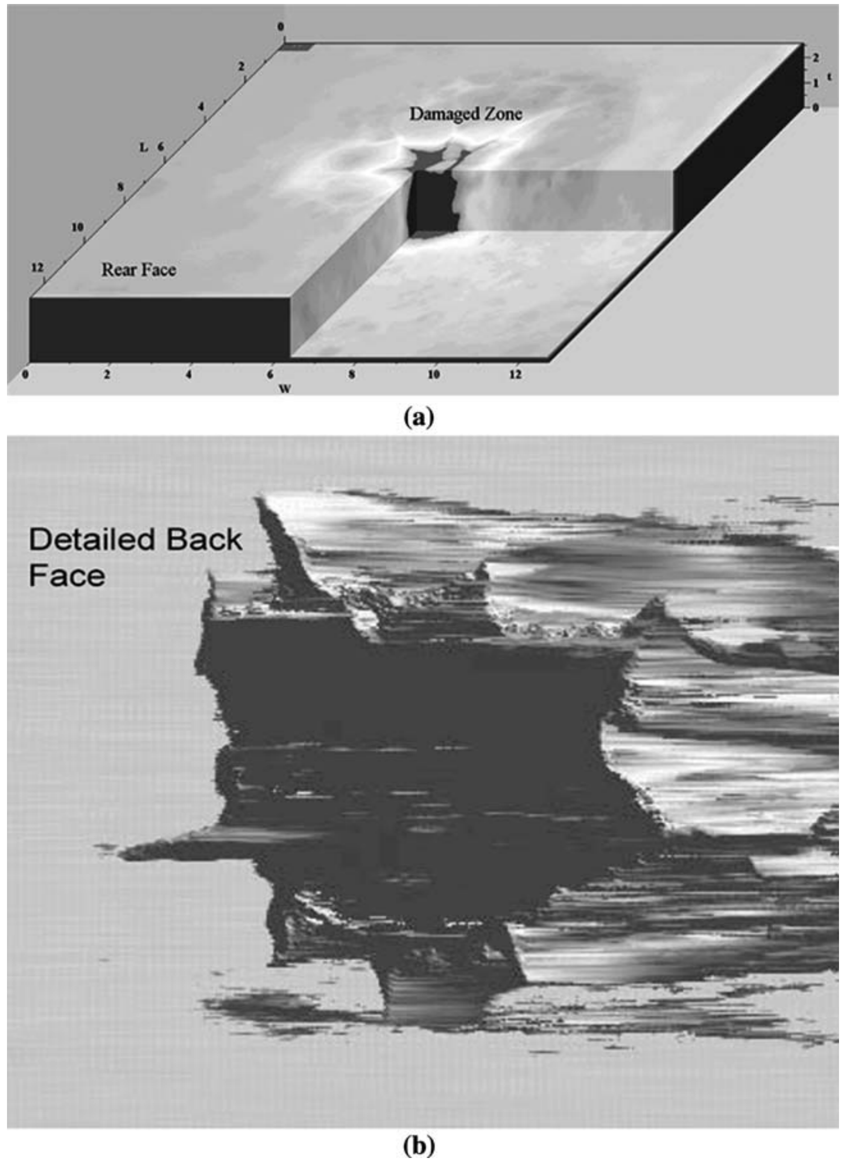


Fig. 5 The sequence of damage in the concrete panel protected by Polypropylene fabric

damage to the back face due to impact loading is shown in the last image in Fig. 5. The size of the damaged region detected by MLX corresponds to the size of the bulge in the PP fabric shown in Fig. 4b. The MLX technique reveals radial cracks emanating from the hole created by the projectile. Whereas in plain concrete panels a deep crater formed on the back surface (see Fig. 3b) due to the removal of concrete material, no such crater formed in PP reinforced concrete panels. Otherwise, the circumferential separation between removed and intact matrix material would show up as dark regions with the MLX technique. Some hairline circumferential cracks are evident at the back face in Fig. 5 but the cracks are discontinuous. With respect to damage evolution due to impact loading, radial crack formations seem to precede crater formation. Such information is critical for the development of damage models. The MLX technique also provides information on the severity of damage through the thickness of the con-

Fig. 6 3D views of damage in concrete panel protected by Polypropylene fabric; (**a**) along the thickness of the panel; (**b**) damage at the back face



crete panel. The largest damage is observed on the back surface and decreases towards the front face. The radial cracks observed on the back face decrease in length and number with increasing distance away from the back face. No damage (except for the hole left by the projectile) is visible after a distance of 18 mm away from the back face.

3D-reconstruction was performed with image J [7] using the images along the thickness of the concrete panel shown in Fig. 5. Figure 6 shows the 3D view of the PP reinforced concrete panel. A block was cut out to show the extent of damage along the thickness of the panels (see Fig. 6a). The damage of the back face in 3D is shown in Fig. 6b. Again, it is clearly observed that the damage becomes more significant when approaching the back face.

Conclusion

Plain and concrete panels reinforced by polypropylene fabric have been subjected to impact loading by a steel projectile. In concrete panels the damage due to impact loading can be visually assessed. In PP reinforced panels, on the other hand, where the damage is obscured by the fabric, motionless X-ray laminography has been employed to give a layer-by-layer view of the damage caused within the concrete panel. These images give information on the variation and extent of damage through the thickness of the concrete panel. The damage to concrete panels protected by polypropylene fabric is considerably reduced compared to plain concrete panels.

References

1. Albert RD, Garrison J (2005) Compos Adhesives Newslett 9
2. Albert RD, Albert TM (1993) Mater Eval 51(12):1350
3. Kennedy RP (1976) Nuc Eng Design 37:183
4. Yankelevsky DZ (1997) Int J Impact Eng 19:331
5. Goldsmith W (1999) Int J Impact Eng 22:95
6. Vossoughi F, Ostertag CP, Monteiro PJM, Johnson GC (2007) Cement Concrete Res 37:96
7. Rasband WS, Image J, U.S. National Institutes of Health, Bethesda, Maryland, USA, http://www.rsb.info.nih.gov/ij/, 1997–2006