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THE EFFECT OF CONCRETE STRENGTH, PRESTRESSING SYSTEM, T-HEADED BARS AND STEEL LINER SYSTEM ON THE PUNCHING PERFORMANCE OF CONCRETE PANEL SPECIMENS SUBJECTED TO IMPACT LOADS

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ABSTRACT

The protection of Nuclear Power Plants (NPP) against aircraft crash impact is a safety requirement and is considered in nuclear regulators and organizations. Candu Energy participated in the internationally organized IMPACT program at VTT's testing facilities in Finland since 2006. After successfully completion of IMPACT Phase I & II testing program, Candu Energy has developed a total of four punching test specimens labelling P7, P8, P9 and P10 as a part of IMPACT Phase III testing program to study a number of parameters affecting local impact behaviour and in particular high-strength concrete which has not been accounted as a significant effective parameter during Phase I and II. All of these specimens including high-strength concrete specimens are reinforced with bending reinforcing bars, T-headed bars and prestressing dywidag rod system. In addition these four specimens have steel liner plate combined with anchorage system. The test specimen is a prestressed concrete panel subjected to a projected hard missile mass with relatively high impact velocity.

The purpose of the above testing program is to demonstrate that a single containment structure will be capable of resisting large commercial aircraft crash impact and meeting both Canadian and international regulatory design requirements. In addition, the result of this testing program can be used in numerical simulations.

This paper presents the experimental results of three specimens, P7, P8 and P9 performed (the specimen P10 in progress) from IMPACT Phase III testing program. In addition, the results of these tests are compared with C2 and C21 specimens from previous IMPACT II testing program in order to evaluate the effects of T-headed bars and concrete strength on the performance of concrete panel specimens subjected to missile impact loads. Successful completion of this program provides technical information to account for the effect of high-strength concrete, prestressing, T-headed bars and liner anchorage system and will be also presented.

INTRODUCTION

To prevent excessive local damage it requires that the barrier be thick enough to prevent scabbing and perforation of the concrete. Overall structural collapse prevented by designing the barrier to have reserve strain energy capacity greater than the total absorbed energy to which it is subjected.

Local effects of missile impact have been studied by several researchers since 1946. The formulas were based upon experimental results for concrete slabs that were perforated by projectiles and bombs to define the penetration depth, perforation and scabbing thickness. These empirical formulas are valid for non-deformable (rigid) missiles and are based on data for lightly reinforced concrete members. The use of these formulas suffers from limitations in the range of available test data. The local response of the target will be initiated with spalling and subsequently result in penetration, scabbing of target material from the back face of the target, and eventually perforating the target (see Figure 1).

Empirical formulas validated by tests have been used to predict these local responses for predominantly rigid (non-deformable) missiles. Empirical formulas are for the case of normal (90 degree) impact. When the impacting missile strikes normal to the target face, the local responses are maximized. The angle of strike can substantially influence the extent of local damage and should be considered to determine the missile velocity component normal to the target face for a maximum impact.

A comprehensive R&D program was carried out at Candu Energy Inc. (a Division of SNC-Lavalin Nuclear) to develop the design methodology to protect containment structure and other safety related structures against malevolent actions to meet performance and functional requirements. As a part of Candu Energy Inc. research activities, this paper presents the experimental results and comparison of three specimens, P7, P8 and P9 (the specimen P10 is in progress) from Phase III IMPACT testing program. In addition, the results of these tests are compared with C2 and C21 specimens from previous IMPACT II testing program in order to evaluate the effect of T-headed bars and concrete strength on the performance of concrete specimens subjected to missile impact loads. Successful completion of this program provides technical information to account for the basic evidence behaviour and effect of high-strength concrete, prestressing, T-headed bars and liner with anchorage system and will be also presented.

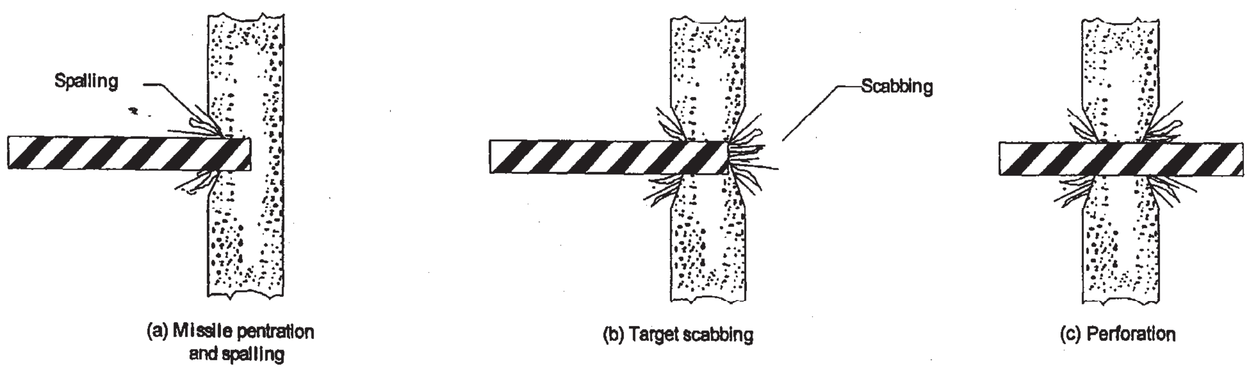


Figure 1. Sequence of Target Local Damage Due to Missile Impact, DOE (1996)

TEST SPECIMENS

The concrete panel specimens (target) have 2.1 m x 2.1 m x 0.25 m thick with 2.0 m span in both directions reinforced with ø 10 mm bars at 90 mm each face and each way with the specified yield strength of 500 MP. Shear reinforcement in the form of T-headed bars were placed at each intersection of longitudinal bars (90 mm in each way). Before casting the concrete, steel liner plate combined with stiffeners in both directions was placed in the form (see Figure 2a). For better understanding the liner mechanism, Candu Energy Inc. has designed steel liner system attached to the test specimen to simulate the containment structure liner system. In addition to longitudinal and shear reinforcement (T-headed bars) prestressing system in the form of Dywidag rods were placed inside the PVC ducts (see Figure 2b and c). The measured concrete strengths for P7 specimen was 46.9 MPa while the measured concrete strength for both P8 and P9 specimen was 79 MPa. After the concrete reach the desirable strength, the specimens were prestressed with equivalent 10 MPa compressive strength in both directions. Figure 2 shows the sequences of specimen preparation before the test.

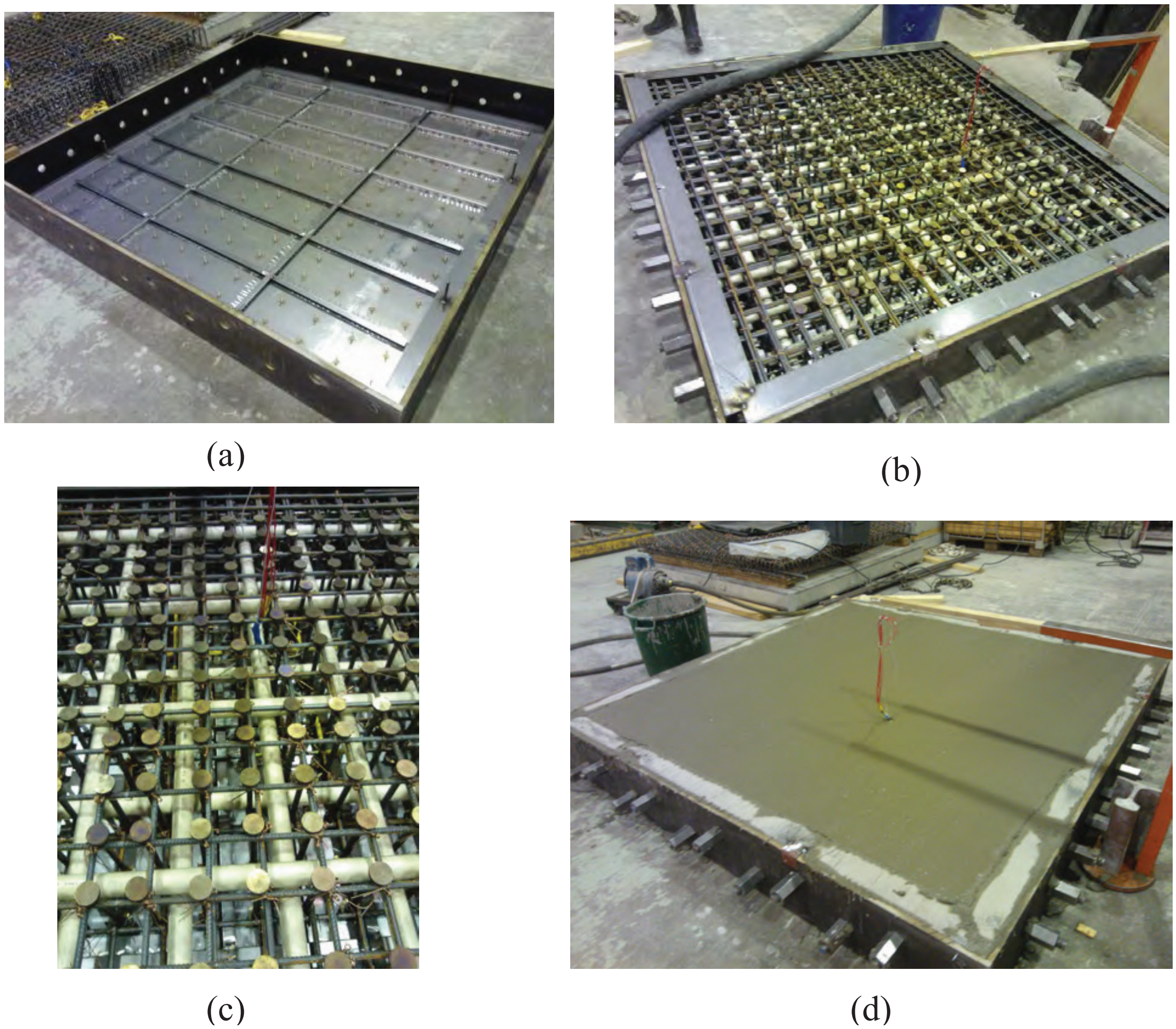


Figure 2. Test specimen with longitudinal reinforcement, T-headed bars, prestressing dywidag rods and liner system

TEST SETUP

A sketch of an apparatus used in testing is shown in Figure 3. The tests are performed using the 169 mm diameter, 47.4 kg hard missile with the specified missile velocity, against the simply supported 2-way prestressed concrete panel specimens as indicated earlier. Figure 4 shows the typical specimen mounted on a frame and ready to be tested

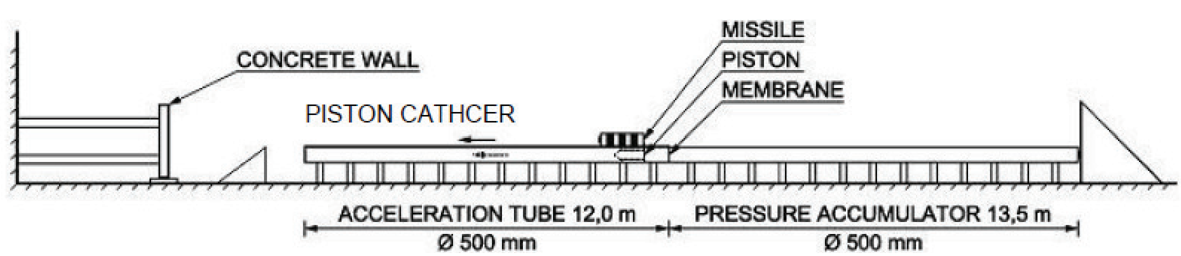


Figure 3. Schematic side view of concrete wall and testing apparatus

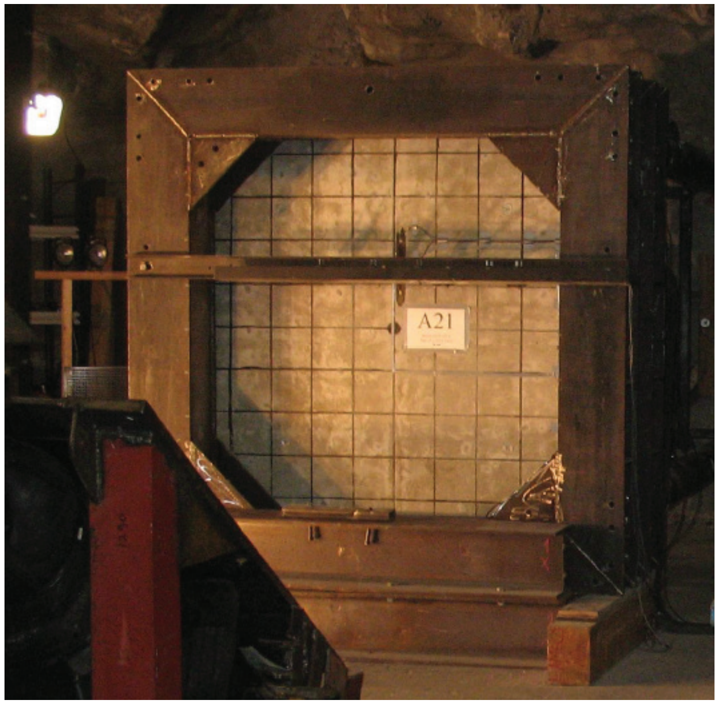


Figure 4. The concrete wall (typical) mounted on frame and ready to be tested for impact load

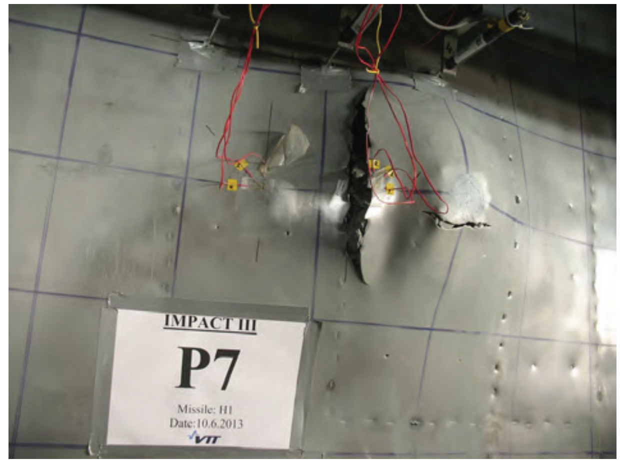
TEST RESULTS

The results of three impact test specimens, P7, P8 and P9 concrete panels subjected to hard missile projectile with specified missile velocity are summarised below. All three specimens have steel liner plate with stiffeners embedded in concrete at the back surface of the concrete panel. In addition, the concrete specimens were reinforced with longitudinal reinforcing bars, T-headed bars and prestressing Dywidag rods.

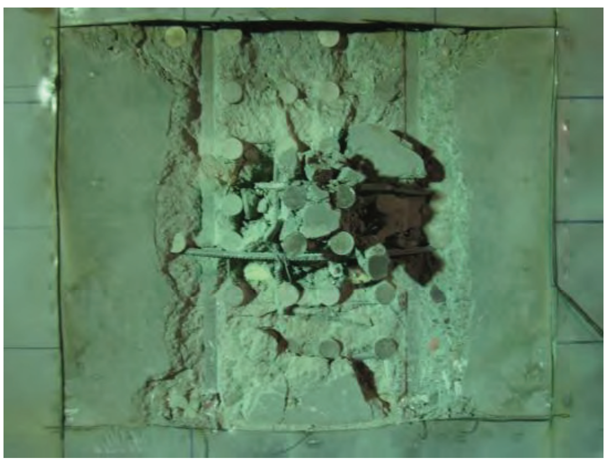
P7 Specimen

Figure 5 shows Specimen P7 after the test. The tested wall had pre-stressing with ungrouted tendons.
The concrete strength at the time of testing was 46.9 MPa measured from concrete cylinders. The specimen was subjected to 112.6 m /s (measured) hard missile velocity. As can be seen, the projected missile penetrated but not perforated into the concrete (see Figure 5(a)). As a result of the test, the missile was stuck between the middlemost prestressing Dywidag rods. When measured after the test, it's penetration into the wall was 160 mm. The liner at the back surface was ruptured in a vertical direction along the welding line of the middlemost vertical stiffener, located 155 mm to the right as can be seen in Figure 5(b). This rupture was roughly 340 mm long. In a similar location on the other side of the hit point, the liner plate and the stiffener had become de-attached at the welds but the plate still remained otherwise intact (see Figure 5(b)). In addition, a horizontal rupture formed also just below the hit point where the T-headed bars had pushed against the liner. The liner still held the concrete scabbing inside it (see Figure 5(c)). Close-up view of liner rupture is shown in Figure 5(d).

(a)



(b)



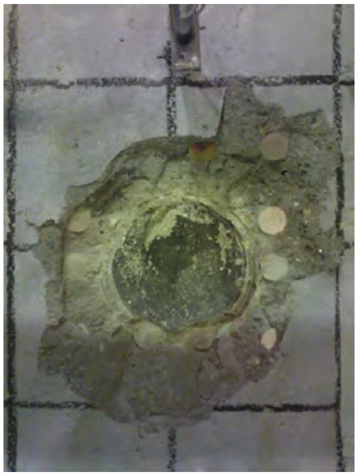
(c)

(d)

Figure 5. Specimen P7 after test; (top-left) missile penetarion at front face; (top-right) liner tearing at the back face; (bottom-left) concrete damage at the back face after removal of the liner; (bottom-right) close-up view of the liner tearing at stiffener-liner plate welding conjuction

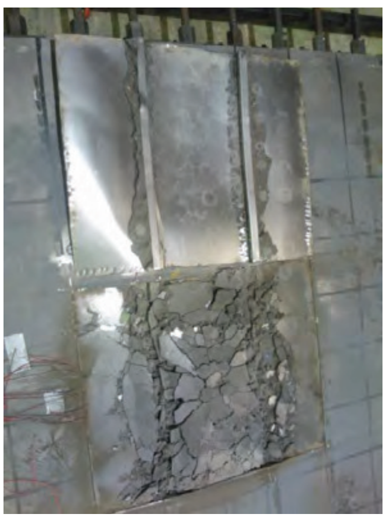
P8 Specimen

Figure 6 shows Specimen P8 after the test. Unlike P7 specimen that had prestressing with ungrouted tendons, the P8 tested wall had prestressing with grouted tendons. The concrete strength at the time of testing was 79 MPa measured from concrete cylinders. The specimen was subjected to 120.4 m /s (measured) hard missile velocity. The missile hit the concrete target with partially penetrating depth of 30 mm and then bounced off (see Figure 6 (a). The liner at the back surface did not rupture and its maximum permanent displacement was 32 mm in the middle (see Figure 6 (b). The liner successfully held the concrete scabbing inside it (see Figure 6 (c) and (d)).

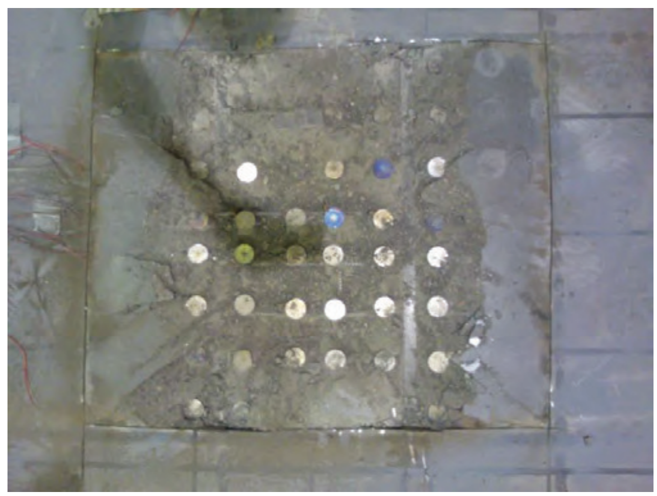


(a)

(b)



(c)



(d)

Figure 6. Specimen P8 after test; (top-left) Partial penetarion at front face; (top-right) undamaged liner at the back face; (bottom-left) concrete damage at the back face after removal of the liner; (bottom-right) close-up view of the concrete after removing the cover

P9 Specimen

Figure 7 shows the specimen after the test. The test was very similar to P8 specimen except the higher missile impact velocity of 140.85 m/s (measured) was applied. The missile hit the concrete target with partially penetrating depth of 47 mm and then bounced off (see Figure 7 (a) and (b)). The liner at the back surface did not rupture and its maximum permanent displacement was 47 mm in the middle (see Figure 7 (c). The liner successfully held the concrete scabbing inside it (see Figure 7(d)).

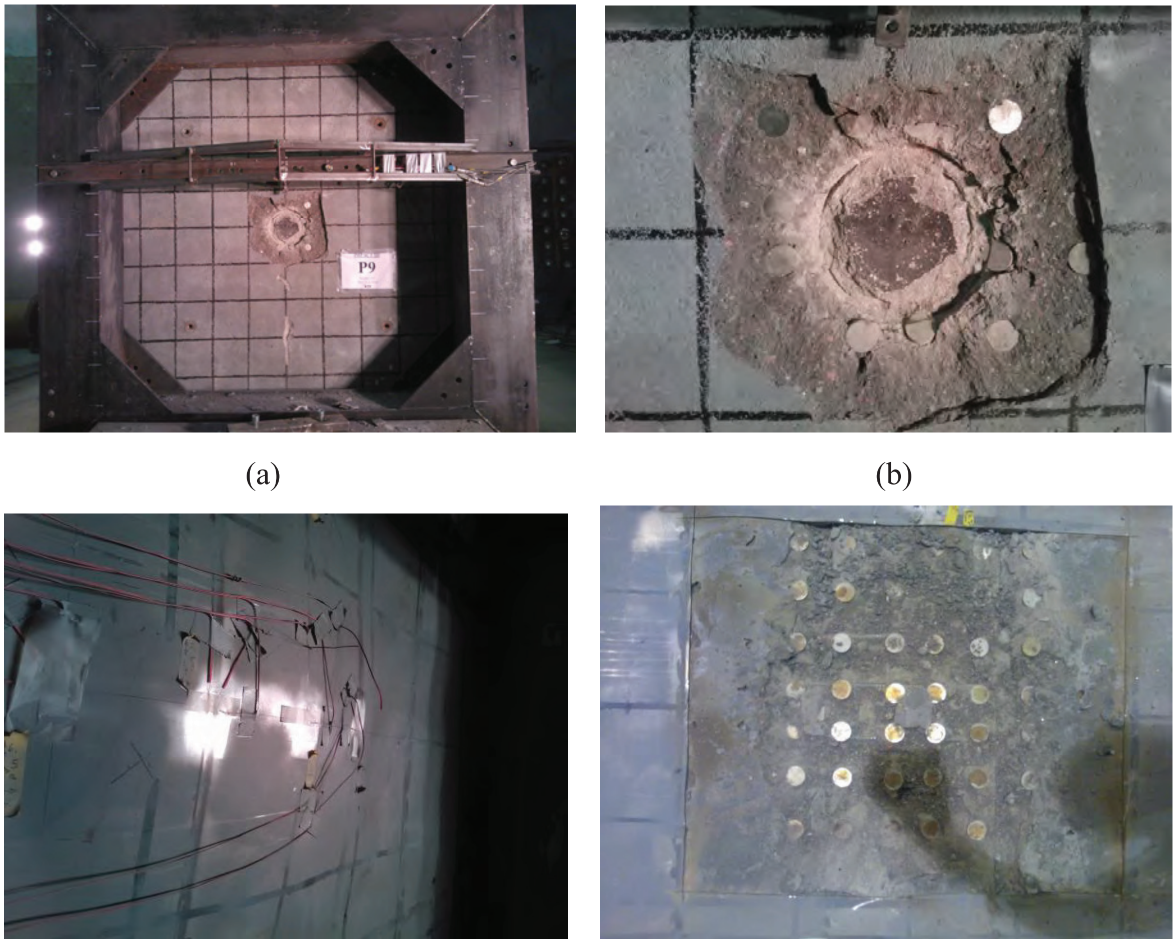


Figure 7. Specimen P9 after test, (top-left) Front face of the specimen after the test; (top-right) close-up view after the missile hit, (bottom-left) undamaged liner at the back face of the specimen; (bottom-right) close-up view of the back face of the concrete after removal of the liner and removal of the concrete cover

EFFECT OF CONCRETE STRENGTH ON P7, P8 AND P9 SPECIMENS DUE TO MISSILE IMPCT LOADS

Figure 8 shows the concrete specimens P7, P8 and P9 after the test. The concrete strength is 46.9 MPa for P7 specimen while both P8 and P9 specimens have 79 MPa concrete strength. As can be seen from this figure, although the missile velocity is lower in P7 specimen the missile penetrated into the P7 specimen with 160 mm penetration depth while due to higher concrete strength in both P8 and P9 specimens the missile hit the concrete target and then bounced off. Similarly, due to the higher concrete strength there was no rupture in liner in both P8 and P9 specimens while due to lower concrete strength there was tearing in liner (vertically and horizontally) in P7 specimen. Figure 8 also shows back face of the specimen after removal of the liner and damage in the concrete. Obviously, the lower strength concrete has larger concrete damage and scabbing comparing to higher strength concrete specimens.

The section cut of these specimens at the location of missile impact is also shown in Figure 8. Due to presence of the T-headed bars diagonal cracks cone shape were observed as expected. However, due to lower concrete strength in P7 specimen than P8 and P9 specimens crack patterns are different with a number of cracks appeared in P8 and P9 specimens.

In addition, due to higher missile velocity in P9 specimen comparing to P8 specimen, although both P8 and P9 specimens have the same concrete strength, the partial penetration of P9 specimen and permanent displacement of the liner are higher than P8 specimens which is consistent and expected.

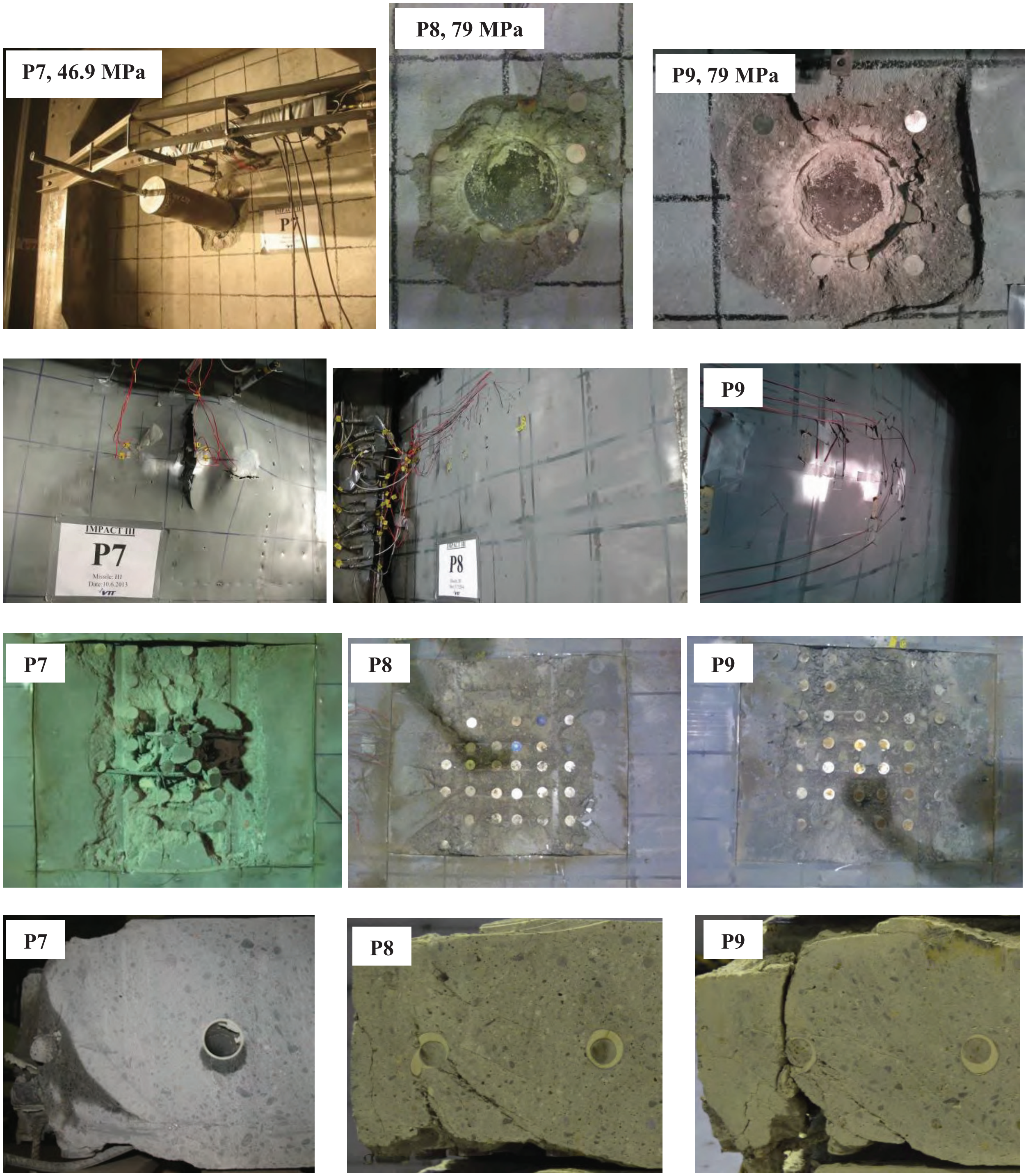


Figure 8. Comparison of P7, P8 and P9 specimens after test; (top) front face of specimens after misile impact; (Middle-top) liner damage and dislacement at the back face; (midddle-bottom) concrete damage at the back face after removal of the liner; (bottom) section cut of the specimens at the impact locations

EFFECT OF T-HEADED BARS ON THE PERFORMANCE OF SPECIMENS DUE TO MISSILE IMPCT LOADS

During Phase I and II of IMPACT testing program many specimens were tested with and without T-headed bars having normal strength concrete. In order to investigate the effect of T-headed bars, Specimen C21from Phase II is compared with P7 specimen of Phase III. Both specimens are prestressed and have the same geometry and longitudinal reinforcement arrangement. In addition, concrete strength and missile velocity are almost similar. C21 specimen does not have any shear reinforcement while P7 specimen contains T-head bars as shear reinforcement. As can be seen from Figure 9, missile was fully perforated into the C21specimen with a large amount of scabbing at the back face of the specimen. On the other hand, the missile was stuck into the P7 specimen with slight scabbing area at the back face of the specimen. There were a number of similar tests showing that the presence of the T-headed bars significantly reduce the scabbing area of the specimens subjected to missile impact loads, Abrishami et al (2013). In addition, during Phase I and II of IMPACT testing program a number of specimens were reinforced with shear reinforcing bars in the form of hooked stirrups but the performance of the specimens due to impact loads was not significantly improved.

Figure 9. Effect of T-headed bars; (left) back face of C21 specimen (no T-headed bars) after test; (middle) missile stuck at front face of P7 specimen containing T-headed bars; (right) back face of P7 specimen after test

EFFECT OF COMBINED T-HEADED BARS AND CONCRETE STRENGTH ON THE PERFORMANCE OF SPECIMENS DUE TO MISSILE IMPCT LOADS

Figure 10 shows the effect of both concrete strength and T-headed bars in comparing to C2 specimen from Phase II IMPACT testing program and P9 specimen from Phase III testing program. Both specimens have identical geometry, longitudinal reinforcement and prestressing system. In addition, both tests have similar missile velocity. The only difference is the concrete strength and the presence of the T-headed bars. C2 specimen has normal strength concrete (54.2 MPa) versus high-strength concrete (79 MPa) used for P9 specimen. In addition, the C2 specimen has no shear reinforcement while P9 specimen contains T-headed bars as shear reinforcement. As can be seen from Figure 10, the missile was fully perforated into the specimen with additional measured 39 m/s residual velocity and large scabbing area at the back face of the C2 specimen. It is concluded that the combined presence of the T-headed bars and higher strength concrete significantly reduce the damage through the specimen and in particular scabbing area.

Figure 10. Effect of combined concrete stength and presence of T-headed bars; (left) Specimen C2 with normal strength concrete and no T-headed bars; (middle) front face of P9 specimen having high-strength concrete and T-headed bars; (right) back face of P9 specimen

CONLUSIONS

This study presented the experimental test results of concrete panels containing prestressing Dywidag rods, reinforced with T-headed bars and liner system subjected to missile impact loads and has led to the following summary and conclusions:

- Candu Energy has developed a number of punching test specimens as a part of IMPACT Phase III testing program to study a number of parameters affecting local impact behaviour.
- All of these specimens including high-strength concrete specimens are reinforced with bending reinforcing bars, T-headed bars and prestressing Dywidag rod system. In addition these specimens have steel liner plate combined with anchorage system. The test concrete panels are subjected to a projected hard missile mass with relatively high impact velocity.
- It has been found that the key factors affecting the improved performance of the prestressed concrete panel under impact loads are “concrete strength” and “presence of T-headed bars” as shear reinforcement.
- Other factors to improve performance are “steel liner” and its anchorage system and combining effects of “prestressing system” with T-headed bars and high-strength concrete.
- Due to the well-designed liner plate and stiffeners, much smaller scabbed concrete pieces will be easily bulged and resisted by back-face liner system
- Penetration depth, scabbing area and liner damage significantly reduce when the prestressed concrete panels are steel lined containing high-strength concrete and is reinforced with T-headed bars
- The above testing program based on key containment design parameters has provided valuable test data so to support our objective to demonstrate that single unit containment structure will be capable of resisting large commercial aircraft crash impact and meeting both Canadian and international regulatory design requirements

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