Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division VI

CRITICAL FACTORS IN PREDICTING SCABBING AND PERFORATION THICKNESS OF EC6 CONTAINMENT STRUCTURE

Homayoun H. Abrishami [1], Xue Ming Han [2], and Azhar Khan [3]

[1] Senior Structural Engineer, Candu Energy Inc. Mississauga, ON, Canada (homayoun.abrishami@candu.com)
[2] Director, Candu Energy Inc. Mississauga, ON, Canada
[3] Manager, Candu Energy Inc. Mississauga, ON, Canada

ABSTRACT

The protection of Nuclear Power Plants against missile impact is a safety requirement to protect the public and required by nuclear regulators. In addition to normal operating loads, the containment structure is designed to withstand loadings from a number of low probability external and internal loads such as aircraft impact. To prevent excessive local damage requires that the barrier be thick enough to prevent scabbing and perforation of the concrete. The formulas predicting the scabbing and perforation were based upon experimental results for concrete slabs that were perforated by projectiles and missiles to define the penetration depth, perforation and scabbing thickness. All of these empirical formulas suffer from limitations in the range of available test data. This paper presents the effect of critical factors on prediction of scabbing and perforation thickness. These critical factors have been developed to the concrete over-strength, T-headed shear reinforcement and dome shape.

As a part of VTT IMPACT I and II R&D program (2012) carried out in Finland the influence of T-headed bars on scabbing and perforation of concrete panels was investigated. The test results also showed the damage and scabbing area are significantly reduced even at higher missile velocity. A modification factor taking to account for the presence of T-headed bars as shear reinforcement is proposed for Scabbing formula.

Empirical formulas validated by tests have been used to predict these local responses are for the case of normal (90 degree) impact. 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. The effective velocity is calculated based on the component of the missile velocity to the perpendicular plane projected from the dome.

A comprehensive R&D program was carried out at Candu Energy Inc. for Enhance CANDU 6 (EC6) containment structure on the development of high-performance concrete to meet performance requirements of the containment structure. Due to the high-quality assurance requirements, the mix design strength is well above the specified design strength. In addition, it is well known that concrete strength is increased with time. The effect of the above concrete over-strength factors are investigated. Concrete over-strength factor can reduce the scabbing and perforation thickness and is considered in predicting scabbing and perforation thickness.

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 is 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. All of these formulas suffer from limitations to use 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 eventual perforation of 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.

The Enhanced CANDU 6 (EC6) is expected to meet the regulatory criteria for two predefined levels of impact load cases in severe and extreme conditions as a part of Beyond Design Basis Treats (BDBTs). However, the criteria requirements do not account for the effect of reinforcement (i.e. reinforcing bars, prestressing tendons and T-headed bars) for the severe load case when the scabbing thickness is considered.

The purpose of this paper is to propose a modification factor applied to the scabbing thickness requirements to the applied empirical formulas. This factor is supported by the interpretation of experimental test results from VTT IMPACT I and II carried out in Finland (2006-present). VTT test results show that the presence of the T-headed bars (used in place of conventional shear reinforcement) significantly reduces the scabbing area of the concrete panels affected by the impact loads and therefore should be credited in design criteria. In addition, this paper presents the effect of concrete over-strength factor to reduce the scabbing and perforation thicknesses obtained from the proposed methodology. The effect of dome shape and missile hit angel on scabbing and perforation thickness is also investigated.

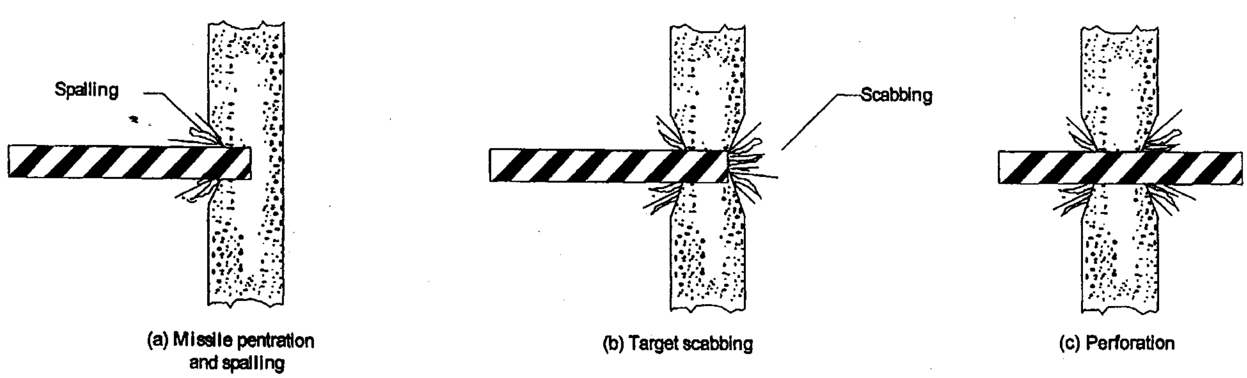

Figure 1. Sequence of Target Local Damage Due to Missile Impact, DOE (1996)

SCABBING AND PERFORATION EMPIRICAL FORMULAE FOR BEYOND DESIGN BASIS TREAT (BDBT$_S$)

Scabbing Formula

As a part of acceptance criteria for the severe accident load case condition**,** the recommended formulae to prevent scabbing are Chang, Bechtel and CRIEPI. If a steel liner is provided on rear surface of the elements, all three formulas have to be applied and the least conservative results should be selected For the impact loads considered for EC6 containment structure the Bechtel Formula (1975) is the least conservative as given below:

$$t_s = \frac{0.015}{\sqrt{f_c^{'}}}\left(\frac{W^{0.4}V^{0.5}}{D^{0.2}}\right)$$

where:

t_s = scabbing thickness (m)

D = effective impact load diameter, (m)

f'_c = concrete compressive strength, (MPa)

W = weight of impact load, (N)

V = Impact load velocity (m/s)

Perforation Formula

For the extreme load case condition, the recommended formula for perforation thickness is the following empirical formula given by CEA-EDF Formula (1990), with an increased factor of 20% due to the scatter of the experimental results:

$$t_p = 1.2x \frac{5.63x10^{-4} W^{0.5} V^{0.75}}{D^{0.5} f'_c{}^{\frac{3}{8}} (R+0.3)^{\frac{3}{8}}}$$

where:

- t_p = Perforation thickness, (m)
- D = Effective impact load diameter, (m)
- f'_c = Concrete compressive strength, (MPa)
- W = Weight of impact load, (N)
- V = Impact load velocity (m/s)
- R = Reinforcement ratio, in one direction, in one layer in percentage

ASSESSMENT OF VTT IMPACT I AND II TEST RESULTS FOR SPECIMENS HAVING T-HEADED BARS

Test Specimens

The concrete panel specimens (target) used in VTT (2012) tests have the specified compressive strength (fc') of 50 MPa reinforced with ø 10 mm bars at 90 mm (A500 HW) each face and each way. Yield strength was theoretically 500 MPa and total elongation was 5.0% at maximum force theoretically. The reinforcement ratio is 0.70% per each direction. T-headed bars were placed at each intersection of longitudinal bars (90 mm in each way). Ø 10 mm bars were used with plates of 30 mm x 30 mm x 8 mm at each end (See Figure 2).

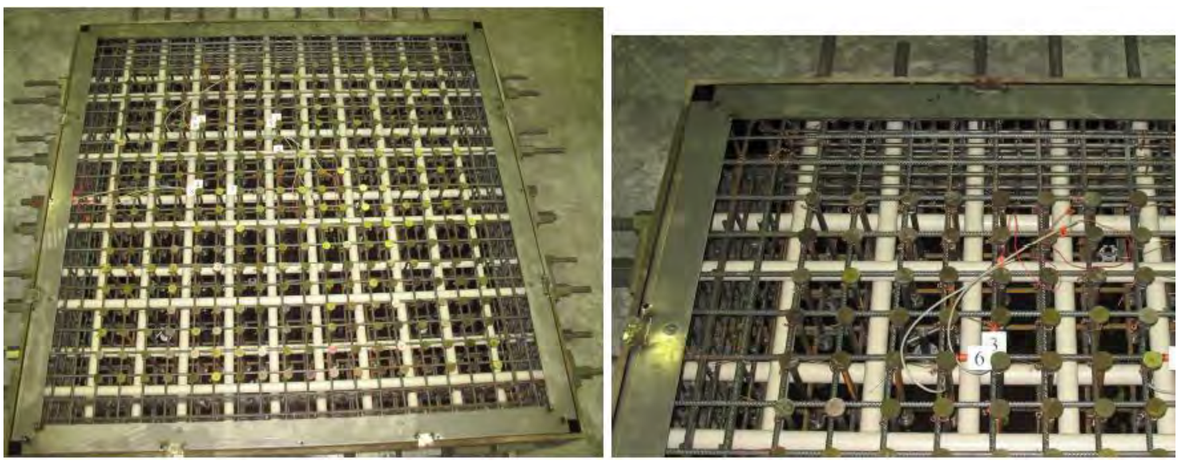

Figure 2. Test specimen with T-headed bars as shear reinforcement

Conclusions from the VTT Test Results

VTT tests showed that the T headed bars significantly reduce the damage particularly scabbing area on the concrete panels due to the missile impact (see Figures 3 and 4). From one series of tests it can be seen that the panels reinforced with T- headed bars at the velocity of much higher (100 to 140 m/s) have less damage than those without T- headed bars with lower velocity (60 m/s). From other series of tests it can be seen that the panels reinforced with T-headed bars at much higher velocity (148 to 152 m/s) have less damage than those without T-headed bars with lower velocity (100 m/s).

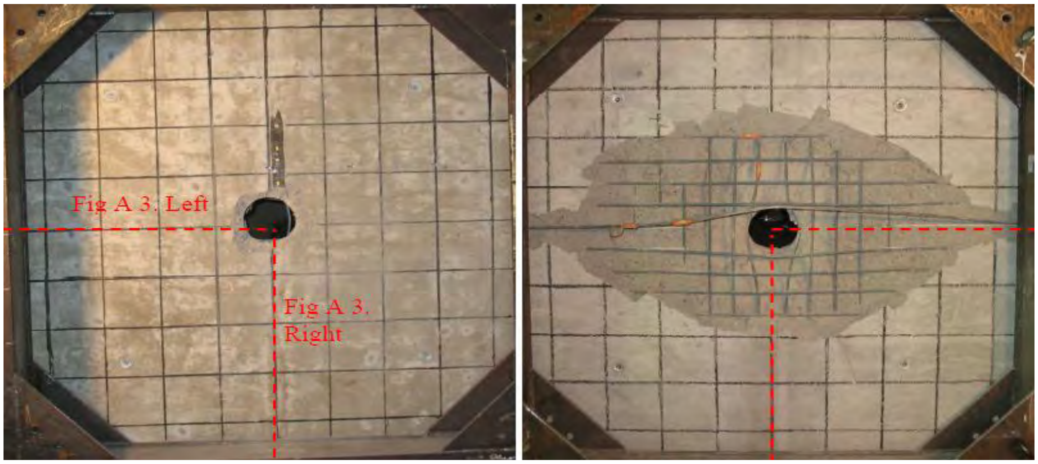

Figure 3. Test specimen without T-headed bars after the test (left-front face, right-rear face)

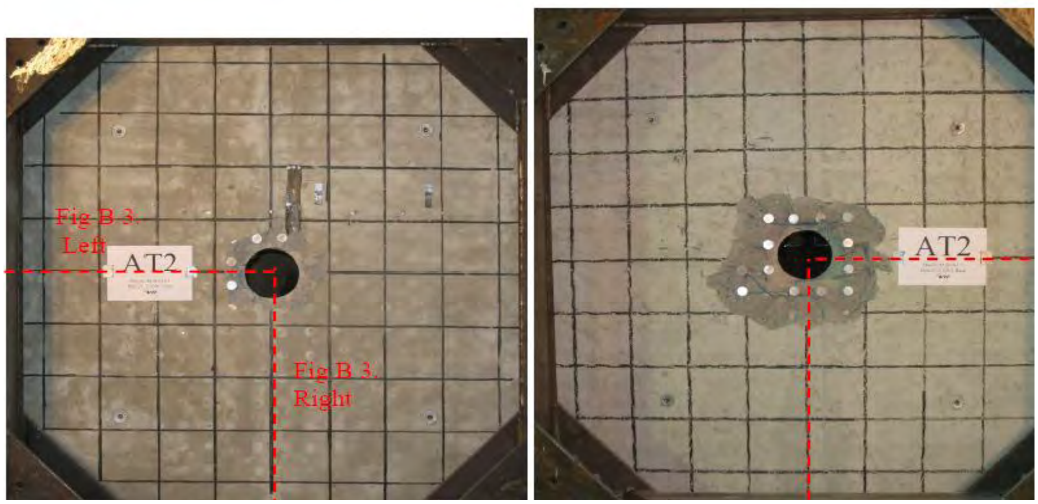

Figure 4. Test specimen with T-headed bars after the test (left-front face, right-rear face)

Equivalent velocity to cause damage to T-headed bar specimens

It has been observed from the test results that the maximum reactions in T-headed bar specimens are significantly higher than specimens having no T-headed bars. This is believed due to the significantly higher stiffness of the T-headed bar specimens and therefore missile Kinetic energy is more transferred to the reaction than absorbed by the T-headed bar specimens. This phenomenon is also consistent with momentum in which velocity has more impact on the reaction force for stiffer specimens. Observing both Kinetic energy and momentum principles it is evident that the stiffness of the specimen has a major role contributing to the damage of the specimens as well as the reaction force. As a result an equivalent velocity for T-headed bar specimens may propose in empirical equations to cause the same degree of damage in specimens without T-headed bars.

EFFECTIVE MISSILE VELOCITY AT CONTAINMENT DOME

In general there are two factors affecting scabbing and perforation thickness of the containment dome. These two factors are the dome shape and the hit angle of the missile. Figure 5 shows the schematic view of the missile hit the dome. As can be seen from this figure, higher hit angle resulted in higher local impact degrees. On the other hand higher the dome angle with respect to the horizontal plane resulted in higher local impact.

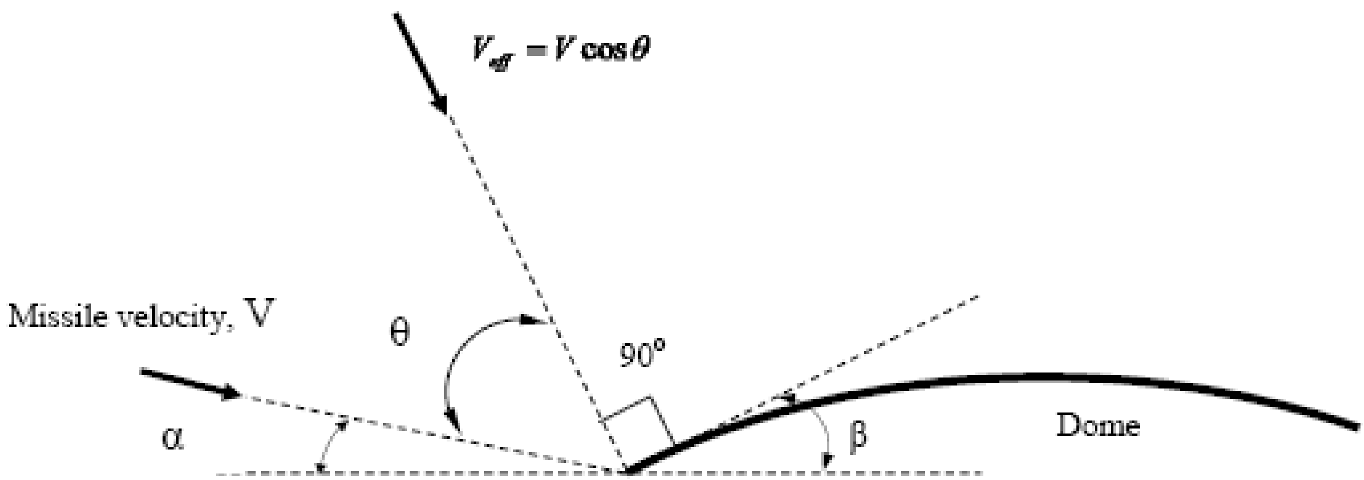

Figure 5. Schematic view of the missile hit the dome at angle α

The effective velocity is calculated based on the component of the missile velocity to the perpendicular plane projected from the dome (see Figure 5). This effective velocity is used to predict scabbing and perforation thickness. Table 1 summarises the calculation for predicting effective velocity.

Table 1. Calculation of Missile Effective Velocity

Missile velocity (V) m/s	**Impact Angle, α**	**Dome angle**	**Effective Angle, θ**	**Effective Velocity (V_{eff}) m/s**
V	α	β	$\theta = 90 - \alpha - \beta$	$V\cos\theta$

Proposed Scabbing Thickness Taking to Account for Presence of T-headed Bars

In order to include the influence of T-headed bars it is proposed to use the equivalent velocity. This reduced velocity that has been obtained from the test results is conservatively proposed as the ratio of the 100 m/s to 150 m's or 0.66. Therefore in the Scabbing formula recommended by CNSC (2011) a reduction factor of 0.66 is proposed to apply to the velocity. Therefore the proposed scabbing thickness is given below.

$$t_s = \frac{0.015}{\sqrt{f_c^{'}}}\left(\frac{W^{0.4}(0.66V)^{0.5}}{D^{0.2}}\right)$$

This equation can be simplified as:

$$t_s = \alpha_T \frac{0.015}{\sqrt{f_c^{'}}}\left(\frac{W^{0.4}(V)^{0.5}}{D^{0.2}}\right)$$

Which:

$\alpha_T = (0.66)^{0.5} = 0.81$, reduction factor due to presence of T-headed bars

CONCRETE OVER-STRENGTH FACTOR

There are two factors contributing the concrete over-strength factor, a) concrete mix design strength and b) strength increase by ageing. Obviously, the existing material strength evaluation and increase strength factor due to concrete mix design strength and ageing should not be used for design basis criteria. However, it is well known in normal practice to use existing material strength for assessment purpose to evaluate the beyond design level. As a result the following two factors described below can only be used for Beyond Design Basis Treats (BDBTs) assessment. Therefore, the designer can take advantage of concrete strength gain due to ageing in the prediction of scabbing and perforation thickness for BDBTs.

Concrete over-strength factor due to concrete mix design strength

According to the concrete technical specification, due to the massive volume of the containment structure and in order to control the heat of hydration, the design compressive strength for the project is 50 MPa at an age of 91 days. The quality control level chosen was that not more than 1% of the results should fall below the design compressive strength and hence the average compressive strength should be the design compressive strength plus the standard deviation times 2.33, ACI-214 (2002). Furthermore, no result should be more than 3.5 MPa below the design compressive strength. For this type of project with very stringent QC, a standard deviation of 3 MPa was assumed for the compressive strength results.

The laboratory trial had a target compressive strength of [50 MPa + 3 MPa (standard deviation) x 2.33]/0.9 (lab factor) = 63 MPa at 91 days. The field trials have a target compressive strength of [50 MPa + 3 MPa (standard deviation) x 2.33] = 57 MPa at 91 days.

A comprehensive R&D program was carried out on development of high-performance concrete and the both laboratory and field trials showed higher compressive strength than predicted [5].

Concrete over-strength factor due to ageing

It is well known that concrete strength is increased with time. For concrete specimen cured at 20 ^{o}C, the CEB-FIP Models Code (1990) gets the following relationship:

$$f_{cm}(t) = \exp\left[s\left[1 - \sqrt{\frac{28}{\frac{t}{t_1}}}\right]\right] f_{cm}$$

where:

f_{cm} (t)	=	mean compressive strength at age t days;
f_{cm}	=	mean 28-day compressive strength
s	=	coefficient depending on the cement type, such as s = 0.20 for high early strength cements, s =0.25 for normal hardening cements, s = 0.38 for slow hardening cements
t_1	=	1 day

The above equation is recommended by Mehta, P. K., and Monteiro, P. J. M (2006). Neville, A. M. (1996) gives a relationship with similar results as the above equation. Although the concrete mix design for containment structure use CSA Type MH (old Type 20) equivalent partially replaced with 50% Blast-furnace slag conservatively s = 0.25 is used in the equation.

From the above equation for the concrete after 5 years (construction period after casting containment concrete to operation time) the concrete strength will be 1.11 times higher than 91 day concrete specified in design. Therefore the concrete strength used in the scabbing and perforation thickness is 57 x 1.11 = 63.3 MPa

PROPOSED METHOD TO PREDICT SCABBING AND PERFORATION THICKNESS

The Candu Energy Inc. proposed method to predict scabbing and perforation thickness considers the two following critical factors:

- The advantage of using T-headed bars
- The advantage of concrete over-strength factor

Scabbing Thickness

As indicated earlier, the proposed scabbing thickness is the selected formula with the reduction factor of 0.81 taking to account for the presence of T-headed bars as:

$$t_s = \frac{0.81x0.015}{\sqrt{f_c^{'}}}\left(\frac{W^{0.4}(V)^{0.5}}{D^{0.2}}\right)$$

Perforation Thickness

The proposed perforation thickness is given below:

$$t_p = 1.2x\frac{5.63x10^{-4}W^{0.5}V^{0.75}}{D^{0.5}\,f'_c{}^{\frac{3}{8}}\left(R+0.3\right)^{\frac{3}{8}}}$$

Concrete over-strength factor can be considered for both scabbing thickness and perforation thickness.

CONCLUSIONS

This study has led to the following conclusions:

- A modification factor taking to account for the presence of T-headed bars is proposed for Scabbing formula. This modification factor resulted in reducing the required scabbing and perforation thickness
- Concrete over-strength factor due to concrete mix design strength and ageing can reduce the scabbing and perforation thickness. However, the concrete over-strength factor shall only be used for impact assessment under BDBTs
- The angle of strike and dome shape can substantially influence the extent of local damage and is considered in predicting scabbing and perforation thickness.

REFERENCES

ACI 214R-02 (2002), "Evaluation of Strength Test Results of Concrete", ACI Committee 214.

Barr, P. (1990), "Guidelines for the Assessment of Concrete Structures Subjected to Impact", SRD R 430, Issue 3.

CEB-FIP Models Code, 1990

Chang W.S (1981) "Impact of Solid Missiles on Concrete Barriers", The Journal of the Structural Division, American Society of Civil Engineers, Vol. 107, No. STD.

DOE-STD-3014-2006 (1996), DOE Standard, "Accident Analysis for Aircraft Crash into Hazardous Facilities", October 1996, Reaffirmation.

Mehta, P.K., and Monteiro, P.J.M. (2006), "Concrete, Microstructure, Properties, and Materials", McGraw-Hill

Neville, A.M. (1996), "Properties of Concrete", Fourth Edition, John Wiley & Sons, Inc.

Ohnuma, H., Ito, C., and Nomachi, S.G. (1985) "Dynamic Response and Local Rupture of Reinforced Concrete Beam and Slab under Impact Loading", Trans. 8th International Conference on Structural Mechanics in Reactor Technology, J5/3

Vassalo, F.A. (1975), "Missile Impact Testing of Reinforced Concrete Panels," Hc-5609-d-1, Calspan Corporation, Buffalo, New York, Prepared for Bechtel Corporation.

Vepsä, Ari (2012) "IMPACT II – Punching Behavior Tests for Simply Supported Reinforced Concrete Walls, VTT Report", (Internal Report)