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Scabbing and Perforation Local Effect of Impactors on Concrete Structures

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Abstract

This paper only deals with the effect of hard missile impact (impacting missile is so stiff that its deformability is negligible to the target deformability) and missile velocity between 28 to 103m/s are considered. Available formulae for prediction the scabbing and perforation thickness of concrete structure impacted by solid missile are summarized and reviewed. Based on statistical analysis of existing data, two new more safe formulae have been proposed for predicting the scabbing and perforation thickness of concrete structures due to impact by solid missiles. The new scabbing and perforation thickness formulae include, missile parameter which are weight of the missile(W), diameter of the missile(D), velocity of the missile (V), and target parameter which are concrete member thickness (t), and concrete member strength (fc'). The simplified formulae for scabbing and perforation thickness of concrete structure impacted by solid missile are presented in terms of penetration depth (Xp). Comparison between present scabbing and perforation thickness of concrete structures impacted by solid missile with other research results are presented.

التأثير الموقعي للتشظي والتثقب تحت تأثير الصدم على المنشات الخرسانية

الخلاصة

هذا البحث يتعامل فقط مع الصدم للقذائف الصلدة (القذيفة الصادمة صلدة بحيث تشوهاته مهملة نسبة الى تشوه الهدف), وسرعة القديفة تتراوح بين 28 الى 103 م/ ث. الصيغ المتوفرة لايجاد سمك التشظي والتثقب للمنشات الخرسانية المتعرضة لقذيفة صلبة تم تلخيصها وعرضها. بالاعتماد على التحليل الاحصائي للمعلومات المتوفرة , تم ايجاد معادلتين جديدتين اكثر امانا لحساب سمك التشظي والتثقب للمنشات الخرسانية المتعرضة لقذيفة صلبة. الصيغ الجديدة لسمك التشظي والتثقب تتضمن معاملات القذيفة والتي هي, وزن القذيفة , قطر القذيفة, سرعة القذيفة, ومعاملات الهدف والتي هي سمك العضو الخرساني, مقاومةالانضغاط للعضو الخرساني. الصيغ المبسطة لسمك التشظي والتثقب للمنشات الخرسانية المعرضة لقذيفة صلبة تم عرضها بدلالة عمق النفاذية. مقارنة بين سمك التشظي والتثقب الحالية للمنشات الخرسانية المتعرضة لقذيفة صلبة مع بحوث أخرى تم عرضها أيضا.

1-Introduction

Effect of impact of solid missiles on concrete structures can be classified into local effects and global dynamic response of the structure. If the kinetic energy transmit through the zone of impact by the missile is considerably smaller than the governing consideration. This paper is concerned with local effects of solid missile impact on concrete structures [(1)].

The problem of impact of missiles on concrete structures is extremely complicated. A complete physical

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modeling of the problem has yet to be developed. However, for design of concrete structures against impact, simple but reliable equations are urgently needed. At present, it appears that only empirical and semi-empirical equations have been developed for design purposes.

Firstly, present the symbols and definitions of terms used in the local effect prediction formulae are presented.

Penetration is the entry of a missile into the target without exiting out of the back face. Penetration may be accompanied by peeling off some pieces of concrete from the back face (with a thickness less than the concrete cover).

Scabbing is the ejecting of the concrete pieces which have at least the size of the concrete cover from the back face and are thrown away from the target.

Perforation is the entry of a missile into the target and its existing out of the back face.

Spalling is the ejecting of the concrete piece from the front face of the target (impact fact).

Figure (1) schematically shows the three types of local effects caused by impacting missiles.

X=observed penetration depth.

Xp=calculated penetration depth.

ds=scabbing thickness; the target thickness which is just enough to prevent scabbing.

d_p=perforation thickness; the target thickness which is just enough to prevent perforation.

The local effect process is influenced by many parameters. These parameters can be classified into two groups; missile parameters and target parameters [(2)], where:

Missile parameters are:

-Weight of the missile (W).

- Size of the missile, e.g., the diameter if it is cylindrical (D).
- Velocity of the missile (V).

While,

Target parameters are:

- Target Thickness (t).
- Concrete strength (compress- ive strength), (fc').
- Steel reinforcement ratio (ρ).

Depending upon whether the missile deformability is small or large relative to the target deformability, the impact missile can be classified as either "hard" or "soft". When the impact missile is so stiff that its deformability is negligible to the target deformability, the missile is considered to be a hard missile (e.g., armor-piercing steel projectiles). When the missile (wooden poles or automobiles) deforms significantly compared with the target deformability, the missile considered to be a soft missile.

This paper is basically concerned with hard (solid) cylindrical missiles.

2- Available formulae for the local concrete damage prediction:

2.1 Army Corps of Engineers formula (COE)[(3)].

The following formula for penetration was developed by Army Corps of Engineers:

$$Xp=D*\{(282WV^{1.5}) / (D^{2.785}fc^{0.5}\ 1000^{1.5}) +0.5)\} \quad \ldots\ldots (1)$$

Where D is the diameter of the missile in inches, W is the weight of the missile in pounds, and fc' is the compressive strength of the concrete in psi.

In 1943 high velocity ballistic tests were carried out on 38,76,and 155mm steel cylinder missiles and the following relationships for predicting scabbing and preforation thickness were obtained using regression analysis[4]:

$ds=D*\{ 2.12+1.36(X_p/D) \}$, for $0.65 \geq X_p/D \leq 11.75$ ……..(2)

$d_p=D*\{ 1.32+1.24(X_p/D) \}$, for $1.35 \geq X_p/D \leq 13.5$ ……(3)

2.2 Modified National Defense Research committee (NDRC) formula:

The National Defense Research Committee (NDRC) proposed the following formula for predicting the penetration depth [1]:

$X_p=D*\{(4KK_1WV^{1.8}) /(D(1000D)^{1.8})\}^{0.5}$ for $X_p/D \leq 2.0$ ..…… (4)

$X_p=D*\{(1.0+(KK_1WV^{1.8}) /(D(1000D)^{1.8})\}$ for $X_p/D \leq 2.0$ ..…… (5)

Where K_1 is the concrete penetrability Factor and is given as function of concrete strength fc' as follows:

$K1=180 \sqrt{fc'}$ ..…… (6)

As defined previously K is the missile nose factor. It is equal to 0.72 for flat nosed missiles, 1.0 for average bullet nose (spherical end), 0.84 for blunt nosed bodies, and 1.14 for very sharp nose.

The proposed equations for predicting scabbing and perforation thickness for use in conjunction with eqs. (4) and (5).

$ds=D\{7.91(X_p/D)- 5.06(X_p/D)^2\}$, for $X_p/D \leq 0.65$ …… (7)

$dp=D\{3.19(X_p/D)-0.718(X_p/D)^2\}$, for $X_p/D \leq 1.35$ …… (8)

2.3 Ballistic Research Laboratory formula (BRL).

The Ballistic Research Labs (BRL) have proposed the following formula to predict directly the perforation thickness for concrete walls having an ultimate compressive strength of 3000 psi.

$d_p=7.8D\{(WV^{1.33}) /(D^{2.8}*1000^{1.33})\}$ ……(9)

This equation has been extended for other values of ultimate compressive strength of 3000 psi as follows:

$d_p=D\{(427WV^{1.33})/(D^{2.8}fc'^{.5}1000^{1.33})\}$ …..(10)

The scabbing thickness ds can be obtained from:

$ds=2dp$ ..…(11)

Table (1) shows the database for missile parameters (W, d, and V) and Target Parameters (t, fc' and Xp) taken from researches, to make statistical analysis to it and then find new modeling of Penetration depth for concrete structures.

Statistical Analysis

Model Definition for penetration depth:

$Xp = (W^{0.704} *D^{0.88} *V^{0.42} *t^{0.84} *fc'^{3.24})^{0.237}$ ………(12)

Where:

Number of observations = 20

Solver type: Nonlinear

Nonlinear iteration limit =250

Residual tolerance =0.0001

Average Residual = 2.84E-12

Residual sum of squares= 7147.01
Durbin-Watson statistic = 2.37
Proportion of Variance Explained = 98.38%, Coefficient of Multiple Determination (R^2) = 0.815
Coefficient of multiple determination (Ra^2) = 0.803

Table (1) shows the the comparison between the X-proposal and X-Experimental from the researches.

In this study, the perforation and scabbing thickness will be taken into consideration, because the effect of penetration without reinforcement concrete structures impacted by solid missile has been proposed in detail in previous research.

Table (2), shows the results of scabbing and perforation thickness for formulae 2 through 11, and proposed formula 15 and 16(noted later).

Statistical Analysis:

A-Model Definition for present perforation thickness:

$$dp = a_2*W+b_2*D+c_2*V+d_2*t+e_2*\sqrt{fc'}+f_2 \quad \text{………..(13)}$$

a_2	4.0E-04
b_2	-0.051
c_2	-8.3E-05
d_2	1.90
e_2	-1.18
f_2	79.90

Number of observations = 20
Solver type: Nonlinear
Nonlinear iteration limit = 250
Residual tolerance = 0.001
Sum of Residuals = 8.52E-13
Average Residual = 4.26E-14
Residual Sum of Squares (Absolute) = 11747.11
Residual Sum of Squares (Relative) = 11747.11
Standard Error of the Estimate = 28.96
Coefficient of Multiple Determination (R^2) = 0.983
Proportion of Variance Explained = 98.35%
Adjusted coefficient of multiple determination (Ra^2) = 0.977

B-Model Definition for present scabbing thickness:

$$ds= a_3*W+b_3*D+c_3*V+d_3*t+e_3*\sqrt{fc'}+f_3 \quad \text{……..(14)}$$

a_3	4.72E-04
b_3	-5.90E-02
c_3	-9.60E-05
d_3	2.19
e_3	-1.36
f_3	92.19

Solver type: Nonlinear
Nonlinear iteration limit = 250
Diverging nonlinear iteration limit =10
Residual tolerance = 0.001
Sum of Residuals = 9.09E-13 Average Residual = 4.54E-14
Residual Sum of Squares (Absolute) = 15639.64

Residual Sum of Squares (Relative) = 15639.64
Standard Error of the Estimate = 33.42
Coefficient of Multiple Determination (R^2) = 0.983
Proportion of Variance Explained = 98.35%
Adjusted coefficient of multiple determination (Ra^2) = 0.977

And the simplified proposal formulae for scabbing and perforation thickness of concrete members presented in this study in terms of penetration thickness are:

$$ds=1.945\ Xp \quad \text{……..(15)}$$

$$dp=2.249\ Xp \quad \text{……..(16)}$$

3- Check the adequacy of new formula for scabbing thickness:

Systematic trend in evaluating the scabbing thickness formula is obtained by matching the predicted result (eq.15) with other researches.

In figures 4 through 7, the horizontal axis represents the calculated scabbing (ds) and the vertical axis represents the thickness of the target (t). Ideally all points which lie below the 45° line on the plot should be test samples where scabbing occurred and points above the 45° line should be test samples where no scabbing occurred. When a formula predicts that, for a certain missile and target, the scabbing thickness is less than the target thickness i.e., the point is above the line 45° line, according to this formula, scabbing should not occur. But, when the results show that scabbing occurred for this target, that means this formula underpredicts the scabbing thickness and it is on the unsafe side. Therefore, from the safety point of view the number of scabbing points falling above the 45° line produce unsafe case of underpredicted, and the number of nonscabbing points falling below 45° produce safe case of overprediction.

The percentage of scabbing and nonscabbing points falling below and above the 45° line to the total number of points are shown in table 3. Table 3 also summarizes the results of figs.4-7.

From figures 4 through 7 and table(3), the following observations are made:

1. BRL and COE formulae are poor in predicting scabbing thickness of concrete structures.
2. The present and NDRC formulae give better prediction of scabbing thickness of concrete structures.
3. The new formula of scabbing thickness is better than NDRC due to provide more safety in comparison with others.
4. Also the new formula has all the points of scabbing thickness below 45 line and there are no points above 45 line (no under prediction), and all the points of nonscabbing thickness are below 45 line which provide more safety and it is very close to 45 line i.e., it is not overpredcting.

4-Check the adequency of new formula for perforation thickness:

1. BRL and COE formulae are poor in predicting perforation thickness of concrete structures.
2. The present and NDRC formulae give better prediction of perforation thickness of concrete structure
3. The new formula of scabbing thickness is better than NDRC due to providing more safety in comparison with others.
4. Also the new formula has all the points of perforation thickness below 45 line and there are no points above 45 line (no under prediction), and all the points of nonperforation thickness are below 45 line which provide more safety and it is very close to 45 line i.e., it is not overpredcting.

Conclusions

1. A new model of penetration depth, scabbing and perforation thickness for concrete members impacted by solid missile is presented.
2. A simplified formula for scabbing and perforation thickness for concrete members impacted by solid missile in terms of penetration thickness is also presented.
3. A comparison of scabbing and perforation thickness of concrete members with other research results is also presented.

4. The new formula of scabbing thickness are more safe in comparison with the other researches due to ratio of scabbing points falling below 45^o line (safe line) was 100% for present scabbing formula in compares with 45%for BRL formula, 15%for NDRC and 100% for COE formula.
5. The new formula of perforation thickness are more safe in comparison with the other researches due to ratio of nonperforation points ratio falling below 45^o line (safe line) was 100% for present scabbing formula in compares with 5%for BRL formula, 80%for NDRC and 95% for COE formula.

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Table (1) Data and Calculated Local Response for Concrete Members Impacted by solid missile [(2)]

Weight (W)	Diameter(D)	Velocity(V)	Thickness(t)	Concrete Strength (fc')	Penetration depth Experimental (X)	Penetration depth Proposal (X)	% of Error Between Xpro, Xexp
3365.04	109.982	28365	299.72	37.329	299.72	294.66	4.094
3335.63	154.94	27145	299.72	39.9303	299.72	321.77	-5.64
2225	304.8	110105	398.78	40.02	398.78	422.25	-7.32
2225	304.8	106140	398.78	40.02	398.78	420.71	-6.89
1566.4	304.8	132980	398.78	33.534	398.78	383.04	3.32
1882.35	304.8	122915	398.78	33.534	398.78	391.91	1.21
2225	304.8	126880	500.38	38.502	449.58	442.52	10.18
1882.35	304.8	143960	500.38	38.502	500.38	435.77	11.41
2941.45	304.8	143045	599.44	36.018	599.44	476.04	19.35
2354.05	199.89	86010	398.78	36.018	398.78	367.80	7.95
2354.05	199.89	71980	398.78	36.018	429.26	361.32	9.71
2941.45	304.8	89060	398.78	36.018	398.78	418.56	-5.46
294.14	199.89	112850	259.08	41.0205	259.08	255.42	1.28
489.94	199.89	111935	259.08	41.0205	259.08	277.96	-7.39
489.94	199.89	137860	259.08	44.505	259.08	291.43	-13.94
294.14	249.93	186965	259.08	34.017	259.08	264.87	-2.46
549.57	277.87	101870	208.28	41.538	208.28	289.14	-39.42
246.08	249.93	308965	259.08	39.0195	248.92	282.65	-12.92
952.3	203.2	65270	304.8	31.395	304.8	279.67	10.15
947.85	203.2	103700	304.8	31.395	304.8	292.67	5.48

Where:
Weight (W) in N , Diameter (D) in mm, Velocity (V) in mm/s, Thickness (t) in mm, Concrete compressive strength (fc') in N/mm^2 and penetration depth (Xp) in mm.

Table (2) Scabbing and Perforation thickness results for concrete member impacted by solid missile

dp COE(3)	Ds COE(2)	Dp NDRC(8)	Ds NDRC(7)	dp BRL(9)	ds RL(11)	dp proposal(16)	ds proposal(15)
402.65	515.55	339.6005	109.61	338.60	677.21	599.16	691.34
395.70	538.15	421.471	372.09	169.28	338.56	593.87	685.24
741.17	1017.8	842.4293	697.93	209.64	419.28	767.14	885.16
733.14	1009.0	837.1681	711.82	199.66	399.32	767.47	885.54
696.81	969.15	817.5672	758.84	147.58	295.17	772.64	891.51
754.67	1032.60	852.6919	669.20	224.29	448.58	773.61	892.63
780.31	1060.72	867.6049	623.29	258.09	516.19	960.78	1108.5
779.41	1059.74	874.3379	600.83	246.98	493.97	959.22	1106.7
578.96	769.37	589.2191	334.85	288.66	577.33	1151.0	1328.1
632.81	828.43	615.7267	207.77	359.71	719.43	779.31	899.20
575.37	765.44	587.3862	342.27	283.85	567.71	780.47	900.55
685.95	957.24	803.1814	788.99	144.82	289.65	773.92	892.99
430.91	607.0	521.2393	527.96	60.44	120.88	504.61	582.24
458.74	637.5	537.6523	494.39	99.59	199.18	504.77	582.42
480.89	661.81	553.5488	454.87	126.13	252.27	498.49	575.18
552.63	774.13	666.4536	630.85	86.89	173.78	504.17	581.73
577.21	819.88	710.336	758.44	54.13	108.27	404.40	466.62
597.31	823.14	707.2663	524.41	132.38	264.77	488.07	563.16
462.36	643.71	538.2502	520.37	104.84	209.69	607.01	700.40
530.06	717.96	579.8336	410.83	193.17	386.34	603.81	696.71

Table (3) Summary of results of scabbing formulae

Formulae	No. of scabbing points falling above 45◦ line and its ratio	No. of scabbing points falling below 45◦ line and its ratio
COE	0%	100%
NDRC	15%	85%
BRL	45%	55%
Proposal	0%	100%

Table (4) Summary of results of perforation formula

Formula	Ratio of preforation points falling above 45° line.	Ratio of non perforation points falling below 45° line.
COE	5%	95%
NDRC	20%	80%
BRL	95%	5%
Proposal	0%	100%

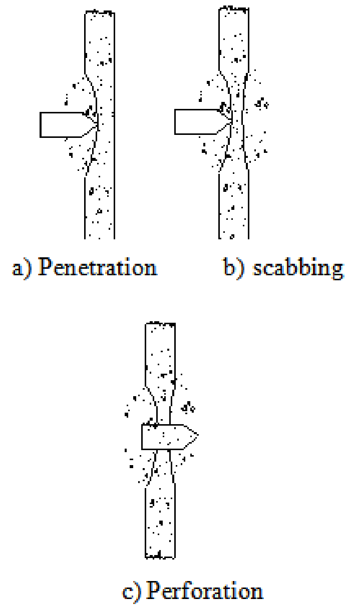

Figure (1) Types of local Figure effects on concrete member caused by impacting missile.

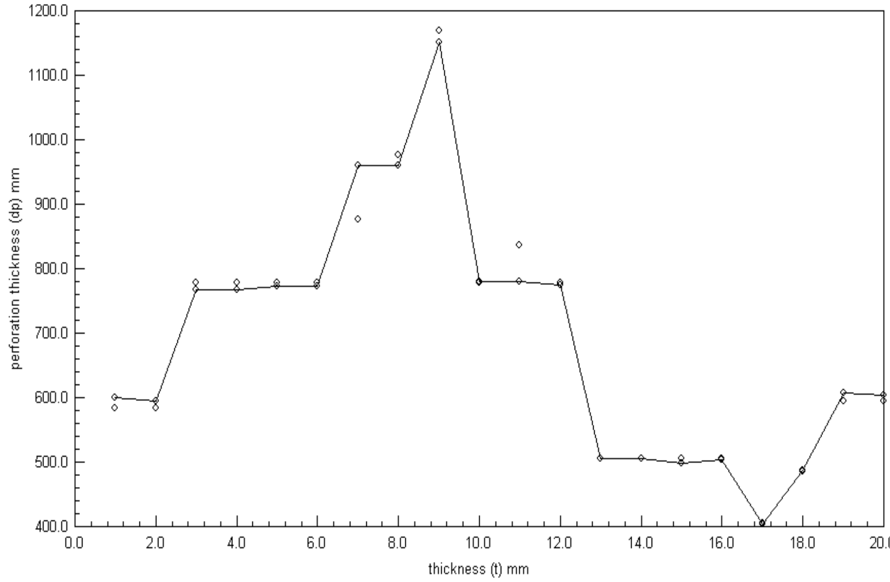

Figure (2) Model proposal of Perforation thickness for concrete member impacted by solid missile

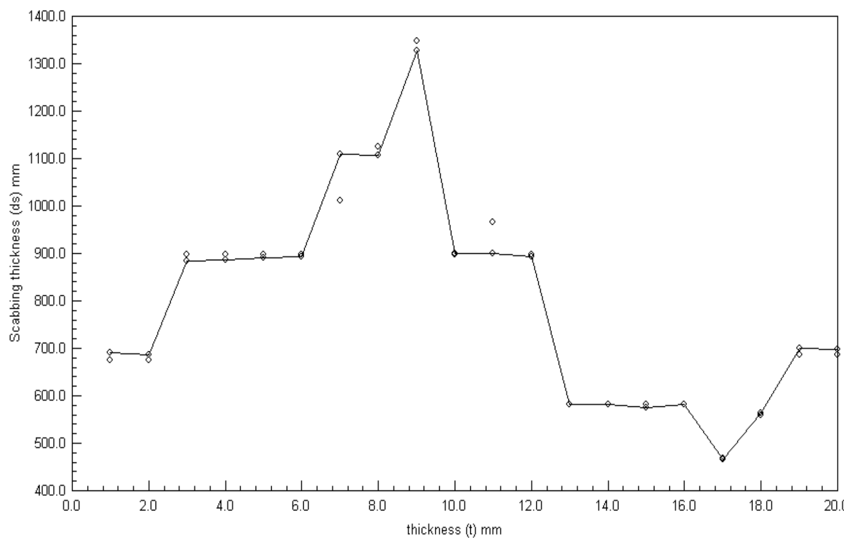

Figure (3) Model Proposal for Scabbing thickness of concrete structure impacted by solid missile

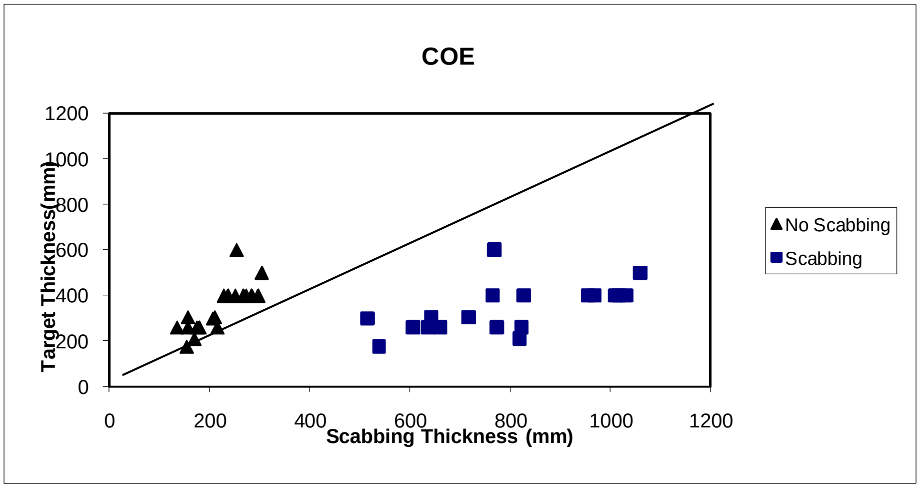

Figure (4) Prediction of scabbing thickness by COE formula.

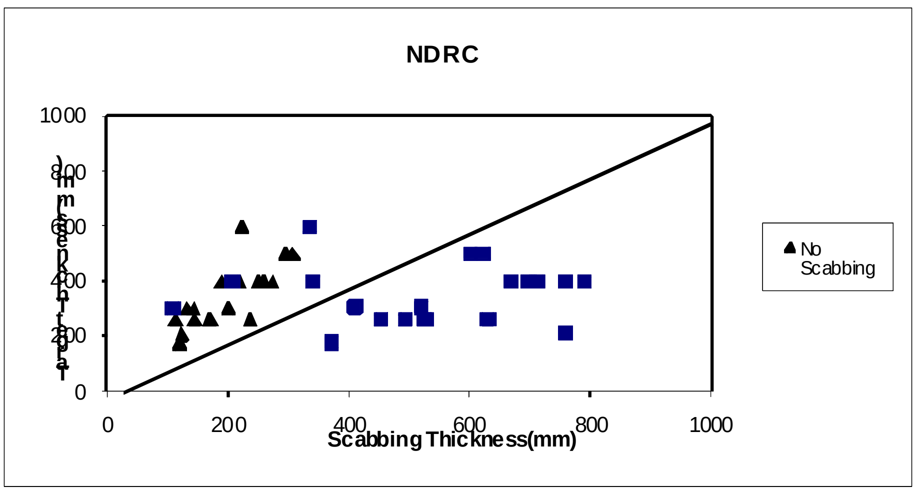

Figure (5) Prediction of scabbing thickness by NDRC formula.

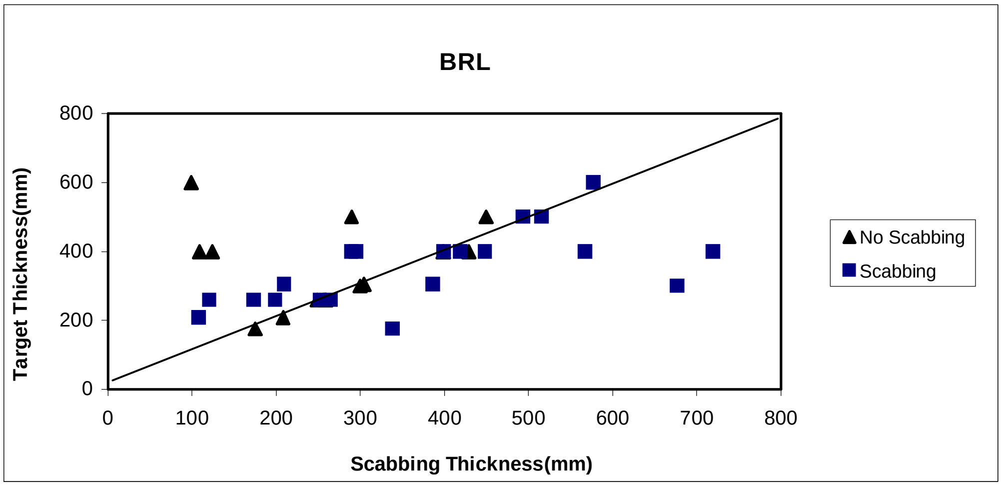

Figure (6) Prediction of scabbing thickness by BRL formula.

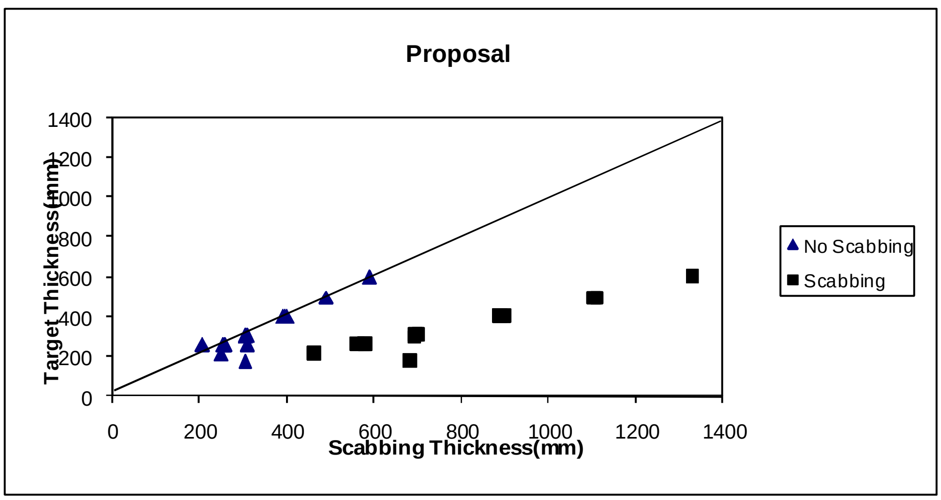

Figure (7) Prediction of scabbing thickness by new formula.

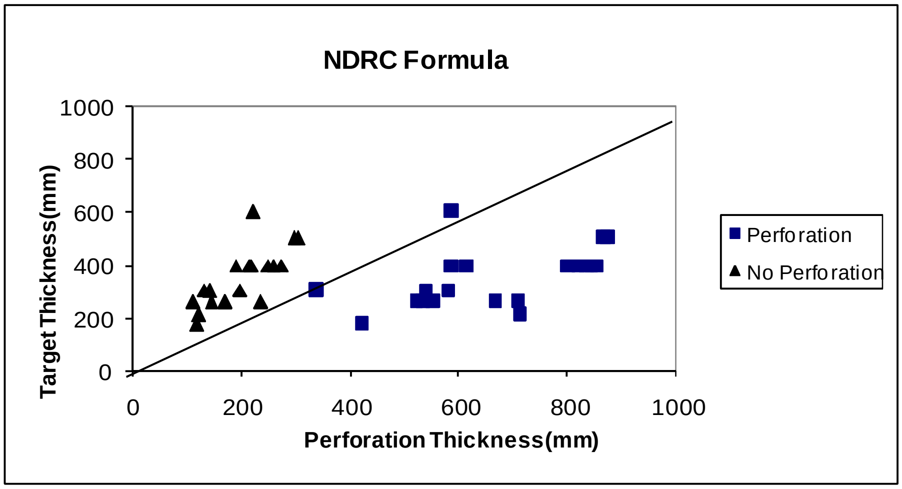

Figure (8) Prediction of perforation thickness by NDRC formula. COE formula.

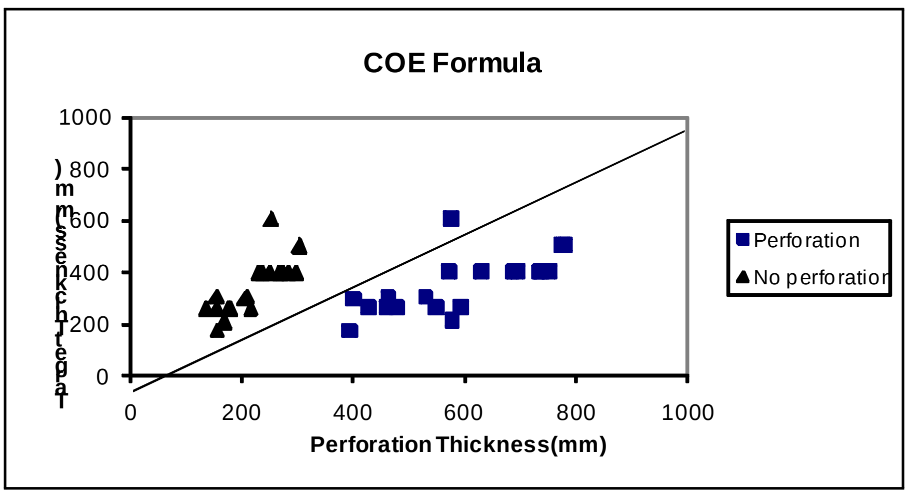

Figure (9) Prediction of perforation thickness by COE formula.

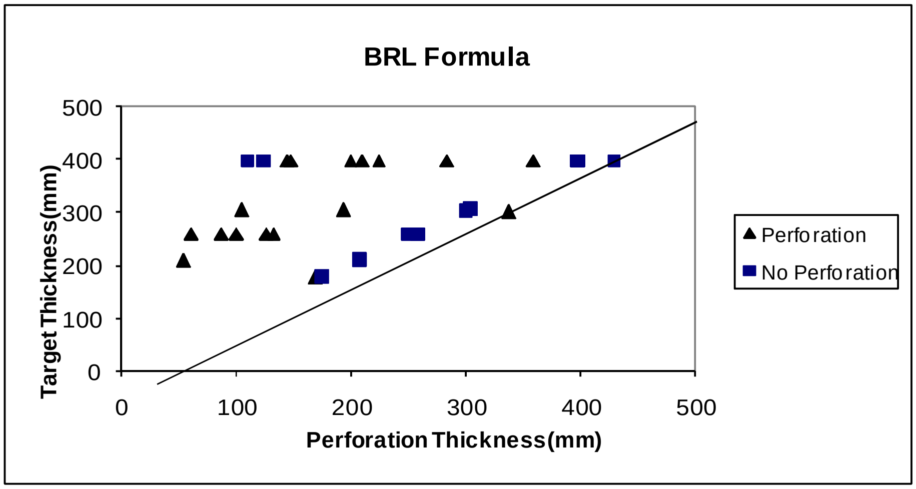

Figure (10) Prediction of perforation thickness by BRL formula

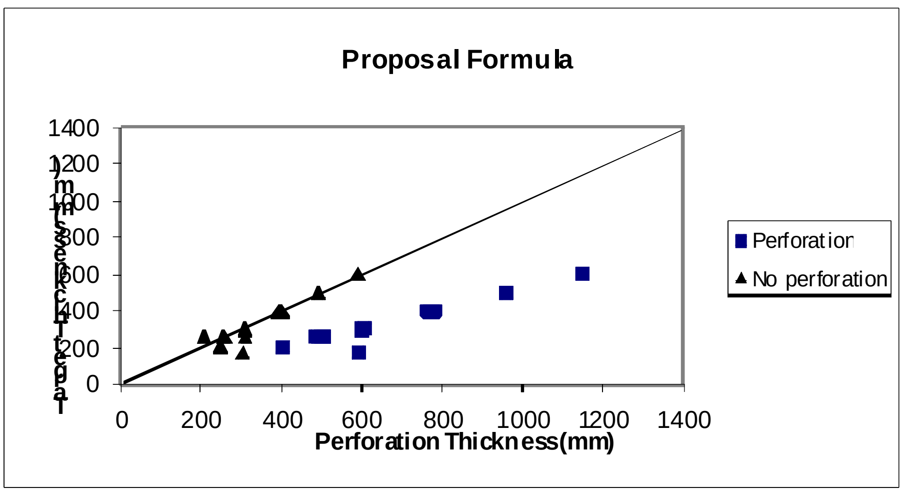

Figure (11) Prediction of perforation thickness by new formula.