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Experimental and Numerical Study on Strength of Concrete Slabs under High Speed Projectiles

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Concrete slab, High speed projectiles, Numerical model, Penetration depth, Crater size.

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A B S T R A C T

Concrete elements under high-speed projectiles effect has an increasing interest recently. Understanding to what extent the concrete can resists the effect of projectiles, very necessary in design structures in order to save the occupants. The objective of this study is to develop improved numerical model for predicting dynamic response of RC slabs under HSP attack. The present study presents a total of 12 concrete slabs casted and tested under plain and steel reinforcement. Parameters investigated were slab thickness, (50 mm, 100 mm, and 150 mm) and projectile type. Dynamic simulation was performed also and the results obtained have been discussed and compared with experimental response. Generally, it was concluded that penetration depth was controlled by target thickness regardless the steel reinforcement. Good alignment achieved between numerical and experimental date with respect to penetration depth and crater vale.

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دراسة عملية ونظرية لمقاومة البلاطات الخرسانية تحت تأثير القذائف عالية السرعة

عمر فاروق قسم الهندسة المدنية/ جامعة ساينس ماليزيا/ بيناغ / ماليزيا

الخلاصة

المنشآت الخرسانية تحت القذائف العالية السرعة لقيت اهتماما خلال الوقت الحاضر. فهم ومعرفة الى اي مدى ممكن للكونكريت مقاومة تأثير القذائف, من الامور المهمة جدا لتصميم المنشآت من اجل حماية محتوياتها. الهدف من هذه الدراسة تطوير نموذج عددي لتتبع التصرف الحركي للعتبات الخرسانية المسلحة تحت تأثير القذائف عالية السرعة. الدراسة الحالية قدمت 12 بلاطة خرسانية تم اختبارها في حالة عدم التسليح والتسليح بنسبة 0.7%. المتغيرات التي تم دراستها هي سمك السقف (50 مم, 100 مم, 150 مم) وكذلك نوع المقذوف. المحاكاة الديناميكية تم انجازها ايضا والنتائج المستحصلة تم مناقشتها ومقارنتها مع التصرف العملي. بصورة عامة, اظهرت النتائج ان عمق الاختراق يعتمد على سمك السقف بغض النظر عن التسليح. تقارب جيد تحقق بين النتائج العملية والنظرية في احتساب عمق الاختراق وقيمة التشظي.

الكلمات الدالة: البلاطات الخرسانية, القذائف عالية السرعة, نموذج رياضي, عمق الاختراق, حجم التشظي.

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1. INTRODUCTION

High velocity projectiles causes severe damages in limited thickness concrete elements, such as walls, and slabs. Attention was increased recently to investigate the response of these structures under high speed projectiles due to increasing in terrorist attack and military usage. The challenging task is to detect the projectile loads and target strength (wall or slab).

The earlier experimental studies discussed the effect of projectile type made by different materials, i.e steel (rigid), copper and lead (flexible) [1, 2, 3, 4, 5, 6, 7, 8]. They concluded that two common types of projectiles, rigid and flexible, plays a great role on the penetration depth value. Zhao et al. [9], Abadel et al. [10], He et al. [11], Wen et al. [12], Ansari and Chakrabartia [13], stated that projectile shape and nozzle velocity has a great role on the penetration value of concrete target. Moreover, it was found that boring size proportional to the projectile velocity.

The effective parameters that examined to check the strength of concrete target against projectile impact were: the thickness, strength and retrofitting of concrete. Liu and Ning [14] showed that plain and reinforced concrete are non-linear, rate-sensitive and pressure-dependent through testing plain and reinforced concrete specimens at different strain rates. Kravanja et al. [15] presented the effect of steel fibers in semi-infinite target to reduce the penetration depth, crater area and volume. Using short steel fibers enhanced the behavior of semi-infinite targets under rifle cartridge 7.62 × 39 mm at the shooting distance of 20 m. Sovják et al. [16] verified through an experimental tests the importance of damage controller of the thin concrete plate due to high speed projectile strike. Their conclusions were based on testing six elements (300 mm× 400 mm× 50 mm) element under 7.62 × 39 mm rifle attack.

To date, the response of concrete members under projectile attack not clearly investigated, especially the effect of target thickness and steel reinforcement- which is the main reason behind the lack in numerical studies. The experimental work, besides being expensive, it has a dangerous nature for this types of researches. From the other hand, increasing the development in computer sciences motivate the researchers to investigate the behavior of high speed projectiles by nondestructive tests. Different methods were used for this purpose can be classified to: empirical method, analytical method and numerical method.

Empirical method considered as the oldest one and it's based on the curve fitting of experimental data [17].

Analytical method used mainly to determine the penetration value and it's based on principal of mechanics and momentum [1].

The last and the modern method is numerical technique. It can be classified also to: Finite Difference, Discrete Elements and Finite Element.

For empirical and analytical technique, various modelling relations and mathematical expressions have been proposed to formulate the behavior of both high speed projectile and target started by Forrestal et al. [17]. Its shown that incorrect material modelling led to clear disagreement between proposed models and experimental data, and incorrect choice of time step can result mismatch in obtained data also [17].

Development in FEM can overtake many problems noted in analytical and empirical simulation problems. Development in material models and a great increase in computer processing speed lead to solve complex problems with good accuracy. Limited research adopted the FE modelling of high speed projectile on concrete structures and this attributed mainly to the lack in experimental data.

Murthy et al. [19] adopted LS-DYNA program to do a nonlinear explicit dynamic analysis by finite element method to calculate the penetration depth of projectile within plain concrete. (238 mm × 25 mm) projectile of three different velocities, 431 m/s, 590 m/s and 773 m/s was modelled with infinite plain concrete target. The penetration depth calculated from this model gives a good agreement with experimental data presented by Forrestal et al. [17].

A three dimensional FE model was developed by Osbolt et al. [20] to simulate fragmentation and high speed impact. The model addressed rate sensitivity, deletion criteria and bulk viscosity. The experimental part contains plain concrete circular plates with three different thicknesses 127 mm, 216 mm and 254 mm. Verification of the model by experimental data show good agreement with respect to failure mode and exit velocity.

The general objective of the present research is to improve FE model to predict the response of RC slabs under high speed projectile effect. To accomplish this features, the present study tests an experimental and numerical behavior to investigate the effect of thickness and steel reinforcement on resistance of concrete slabs under HSP. The parameters tested were: slab thickness, reinforcement ratio, and weapon type.

2. EXPERIMENTAL STUDY

2.1 High speed projectiles

Two types of flexible ogive-nose projectiles were tested by rifle AK-47 and HK-93. These cartridge types represent the most common projectiles of lightweight gun. Physical and mechanical properties of the two projectiles reviewed in Table 1 below [17], while the shape was shown in Fig.1

Table1
Properties of the projectiles [17]

Type	Mass (g)	Length (mm)	Diameter (mm)	Muzzle Velocity (m/s)
AK-47	7.9	39	7.62	700
HK-93	10	51	7.62	900

Fig. 1 HK-93 and AK-47 cartridge

2.2 Target specimens

The specimens were square concrete slabs with dimensions of 500 × 500 mm and different thicknesses: 50 mm, 100 mm and 150 mm i.e the slab behavior changed from thin to thick slab behavior.

The concrete mix was designed according to the American mix design method (ACI-211.1-91) for normal concrete to get a target design strength of 25 MPa at 28 days. The quantities of mix used as shown in Table 2 below.

Table 2

Concrete mix design materials

Water kg/m3	Cement kg/m3	Sand kg/m3	Gravel kg/m3	Compressive strength MPa	Slump mm
182.4	362.5	800.5	900	25.4	74

Specimens were reinforced by 6 mm steel bars tested in laboratory to record a tensile strength of 420 MPa. The steel bars were placed by two layers within reinforced specimens with a rectangular mesh.

The concrete slabs were designed according to the ACI Code 318-19, section 8 for requirements of minimum dimensions and reinforcement (ACI 318-19). Three different thicknesses were adopted, with plain (0%) and (0.7%) reinforcement ratio, this ratio was about twice ρ_{min}. Fig.2 show the reinforcement details and casted specimens for 50 mm slabs.

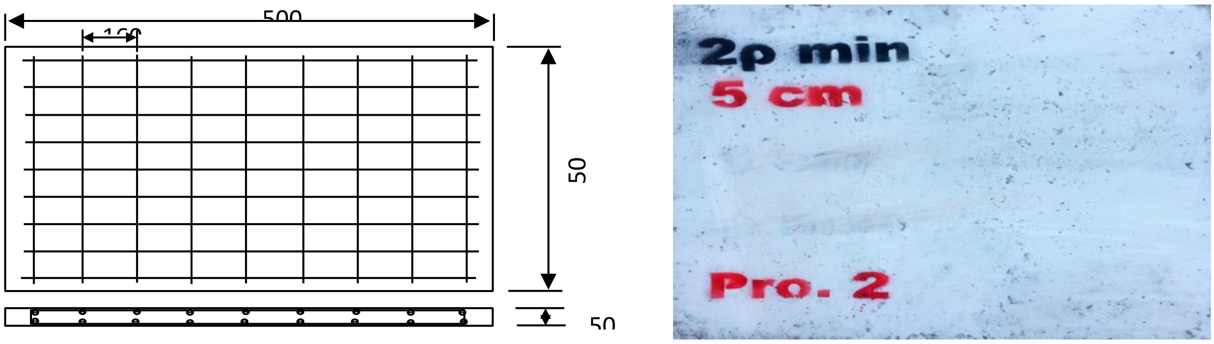

Fig.2 Reinforcement details and casted specimen of 50 mm slab.

All specimens were casted in laboratory, cured in water to 28 days and coded as shown in Table 3. The specimens subscripted as followed Si-j-k, where S: concrete specimen, i: reinforcement ratio, j: thickness and k: gun type.

Table3

Specimens' properties

Specimen No.	Slab Thickness (mm)	Reinforcement ratio (%)	Concrete compressive strength (Mpa)
S0-50-AK	50	0.0%	25.5
S.7-50-AK	50	0.7%	24.3
S0-100-AK	100	0.0%	26.1
S0.7-100-AK	100	0.7%	24.6
S0-150-AK	150	0.0%	25.3
S0.7-150-AK	150	0.7%	24.7
S0-50-HK	50	0.0%	24.8
S0.7-50-HK	50	0.7%	26.3
S0-100-HK	100	0.0%	26.1
S0.7-100-HK	100	0.7%	27.0
S0-150-HK	150	0.0%	25.3
S0.7-150-HK	150	0.7%	24.7

2.3 Test procedure

The specimens were fixed in vertical position 20 m away from gun nozzle. The nozzle was kept straight horizontally to the center of target. All the specimens were fixed at bottom edge while other edges kept free. The penetration depth, crater size and corresponding diameters was measured by electronic scale as explained by Fig.3.

Fig. 3 Recording the crater size and penetration depth.

3. NUMERICAL MODELLING

ANSYS workbench (ANSYS WB) was activated in the present study to achieve the numerical part. 3D explicit dynamic analysis was implemented through the following steps:

3.1 Element type and material properties

Reinforced concrete is a composite material made of concrete and steel. These two materials have different physical and mechanical properties, so they are modeled separately then combined to describe the behavior of the reinforced concrete material. Concrete slab was modeled by 8 nodes brick element with 3 degrees of freedom for each node (x, y and z). Steel reinforcement bar modeled by 3D spar link, while the projectile modeled by hexagonal 6 nodes element. Discrete modelling technique was used to represent the steel bars within concrete. In this case, the bar element will share same node with concrete element as explained in Fig. 4. The multilinear stress-strain curve shown in Fig. 5 was adopted in the present study to model the compressive strength of concrete. On the other hand, the bilinear stress-strain curve was used to model stress-strain curve of steel reinforcement, see Fig.6.

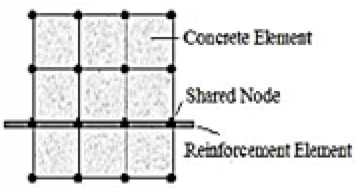

Fig.4 Discrete model

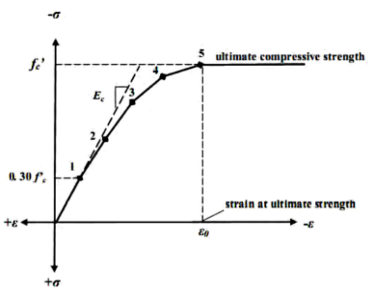

Fig. 5 Concrete model

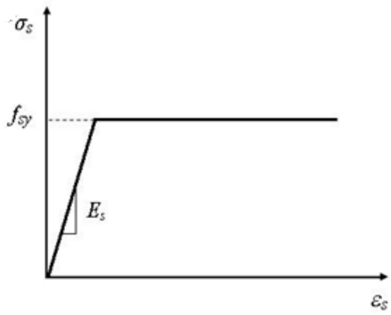

Fig. 6 Steel model

RHT model (Reidel-Hiermaier and Thoma) presented by *ANSYS WB* was adopted in the present study to define the damage evolution and residual strength of the concrete under high speed projectile effect [21].

3.2 Element size (meshing)

Mesh size is an important parameter that must be considered in numerical model creation. It has been reported in literature that mesh size have a significant effect on convergence time and accuracy [24].

In the present study, one-quarter of the tested slab was considered, to benefits from symmetry about two axis, then consuming in time and memory space.

Hexagonal element that was achieved by a function in ANSYS WB was adopted to generate a mesh in projectile and target. Edge sizing and edge functions was used in the contact region between bullet and slab. Modelling for slab and bullet was shown in Fig. 7 for 100 mm slab thickness. Element size edge was chosen to be 10 mm for concrete slab.

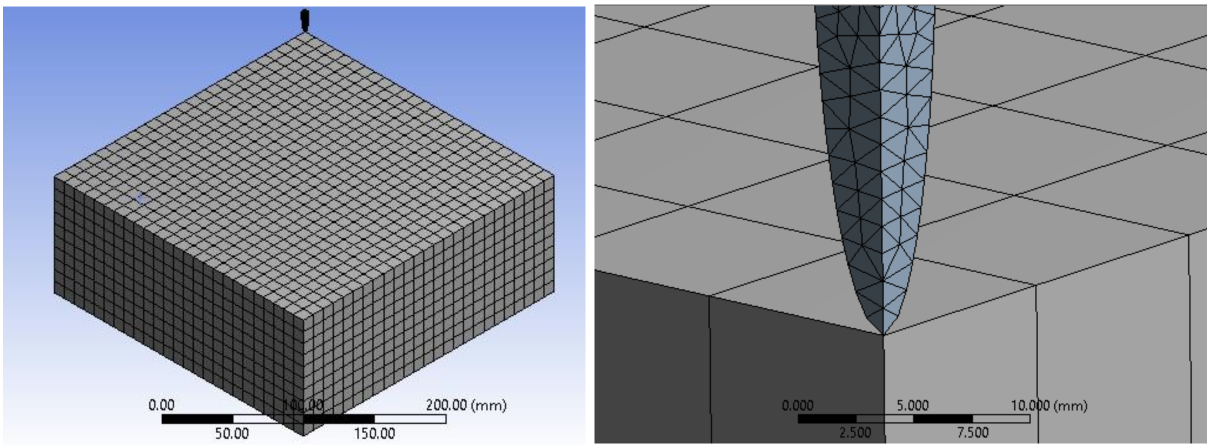

Fig.7 Slab and projectile meshing

3.3 Boundary and initial conditions

Two slab faces parallel to the projectile trajectory and farthest from impact zone was fixed, while other two faces intersecting at impact point (in plans of symmetry) not restricted see Fig. 8.

The loading was applied at impact point and modeled through the definition of projectile's momentum (mass and velocity). Initial velocity of projectile was selected for each type according to Table 1.

The contact type called "automatic contact with penalty method", was chosen to control the contact condition between projectile and concrete target. *ANSYS WB* was provided this utility and its used for high velocity simulation.

Iteration number was set to maximum value of 10^7 with a time step 0.8*ms* at an end time of 0.1 *s*.

Time step was chosen according to the time required for propagation of sonic wave within smallest FE length [21]. When all the dynamic phenomenal ended, the end time was considered.

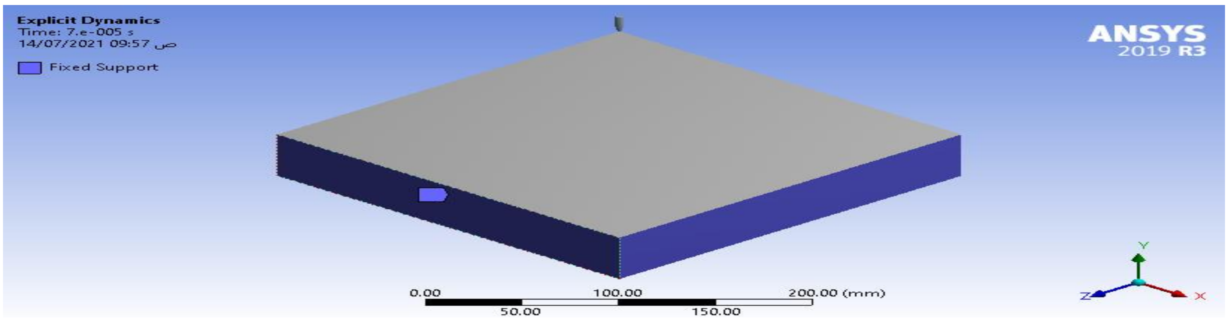

Fig. 8 Fixed supports and projectile impact loading.

3.4 Simulation model

Dynamic behavior of brittle materials is somewhat complex and still under research. Several widely used concrete models is HJC model and RHT model. RHT model (Riedel-Hiermaier-Thoma) is an extension for the HJC, which is give a description of damage independent on plastic volume strain. High strain rate problems can be taken into account using RHT model by amplification factor. The option of this model was provided by *ANSYS WB* for modelling the concrete under projectile strike. Predefined material properties of lead was provided by *ANSYS WB* as required in Table 1. The most important properties utilized when concrete subjected to impact load is: compressive strength, tensile strength, shear strength, shear modulus, density and strain rate for tension and compression.

3.5 Erosion

Failure and time step erosion criteria was adopted in the present model. The erosion algorithm utilized for concrete to account physical erosion of part of slab due to shear, crater formation and fracture. This criteria was implemented also by *ANSYS WB* and its depends on the strain rate, plastic strain and time step consideration [18].

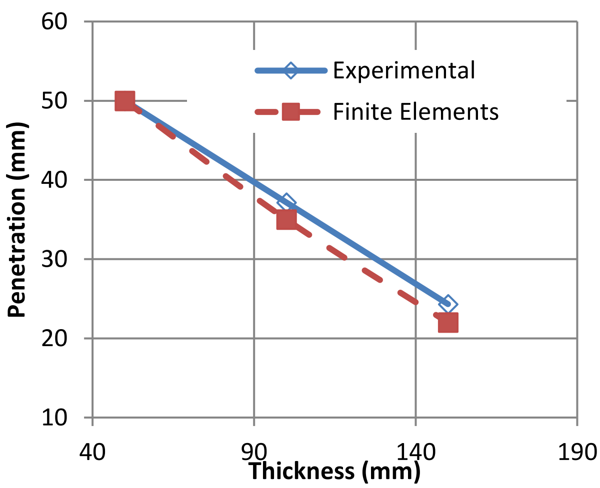

Fig. 9. Penetration-thickness curve for plain concrete specimens under 700 m/s velocityFor this reason, linear relationship can be drawn between penetration value and concrete slab thickness under constant speed value of projectile.

4. RESULTS AND DISCUSSION

In the following section, the response of high speed projectile will be discussed when strike with plain and reinforced concrete slab. The experimental data collected will be compared with numerical one obtained by FE method.

4.1 Penetration value

4.1.1 Plain Specimens

Visible damage occurred in all of the tested specimens. One of three targets was perforated while the others resisted the penetration. Its noted clearly that specimens thickness have a great effect on the penetration value of the plain concrete slab under high speed projectiles as shown in Fig.9 below. Compared to the control specimen, the depth of penetration value was dropped by about 16% when the thickness increased by 50% which is less than 1/3 of the target thickness. Increasing the thickness of the target by about 100% gives an improvement in penetration resistance to 35%. This value was less than 1/6 of the target thickness. Cause neglecting the effect of compressive strength of concrete, this response can be attributed mainly to the increasing in bulk density of the specimen which is lead to the decrease in momentum of the bullet [21, 22].

Finite element simulation can predict very well the penetration values of the plain concrete slabs under AK-47 rifle attack (i.e under 700 m/s velocity projectile). Due to homogeneity of the numerical model, the numerical data looks to be stiffer than experimental one. This trend increased due to slab thickness increase i.e increasing concrete mass.

The penetration values was increased slightly under HK-93 rifle cartridge attack, as explained in Fig. 10. Although the projectile velocity increased to 900 m/s with constant shooting distance, the penetration values not increased greatly due to the increase in projectile mass.

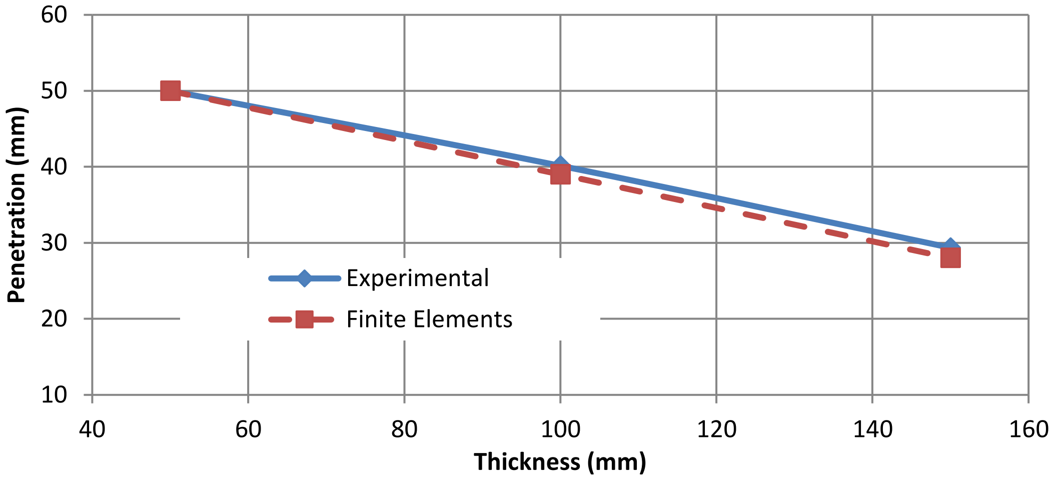

Fig. 10. Penetration-thickness curve for plain concrete specimens under 900 m/s velocity projectile

The full penetration case (perforation) for 50 mm slab thickness was detected perfectly by FE analysis under 700 m/s and 900 m/s projectile velocity (i.e AK-47 and HK-95 rifle, respectively) due to progressive effect finite element erosion. Slight disagreement between experimental and numerical data was noted for specimens under 900 m/s speed as shown in Fig.10.

4.1.2 Reinforced specimens

Steel reinforcement addition to the concrete specimens showed limited improvement on the penetration strength under AK-47 projectile attack of 700 m/s. The percentage of improvement in the penetration strength of slab was limited to 6% over that gained by increasing slab thickness to100 % (see Fig. 11).

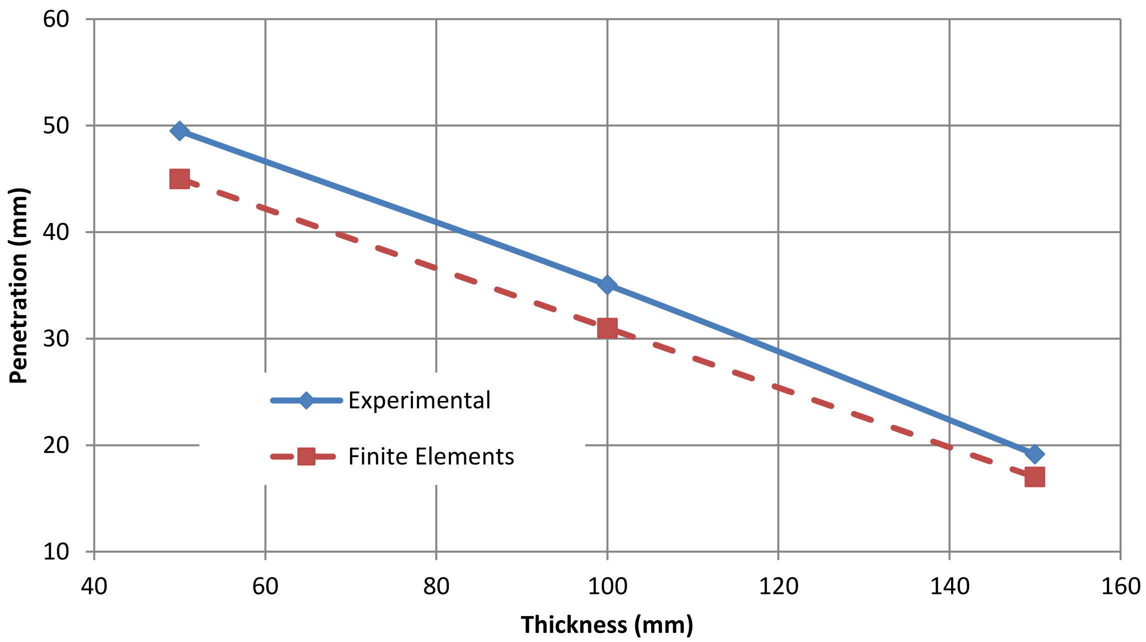

Fig. 11. Penetration-thickness curve for reinforced concrete specimens under 700 m/s velocity projectile

Steel reinforcement reduced mainly the fragments size due strengthening the of concrete specimen surface and considerably reduced the scabbing damage of the RC slab. This is means that the projectile energy dissipated mainly by the concrete adhesion.

RHT material model provided by *LS Dyna* of *WB ANSYS* gives a suitable simulation of projectile impact on concrete material. The mismatch noted in Fig.11 between two studies in comparison to plain concrete specimens can be attributed to the full interaction assumption between steel bars and concrete in addition to the homogenous isotropic assumption for the FE model which is gave that discrepancy.

However, the model gives a good tracing and description for the reinforced concrete slab under high speed projectile strike. Fig. 12 shows a full penetration phase in FE model comparing to experimental test for reinforced concrete slab with 50 mm thickness. In comparison to the plain specimens, the target did not split into several pieces after projectile strike, so the reinforcement keeps the consistency at full penetration (perforation). Erosion criteria based on material failure, plastic strain and damage gives rational results for penetration modelling of projectile within the concrete target.

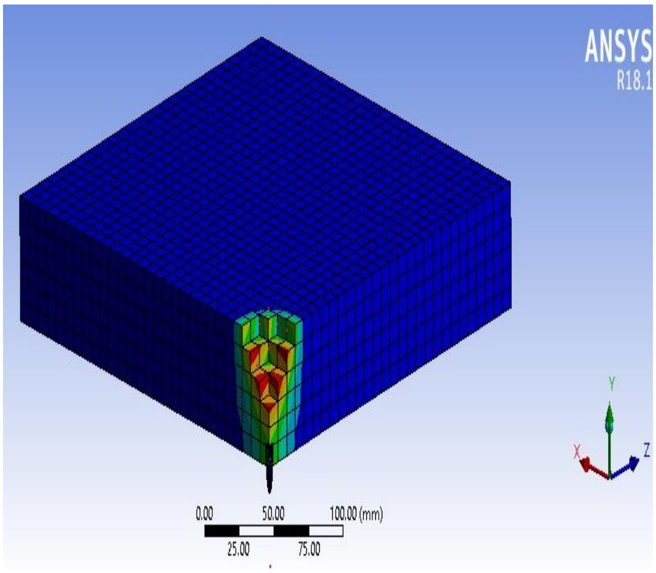

Fig. 12. Experimental and FE penetration illustration

In comparison to plain specimens and when the target attacked by HK-93 high speed projectile, steel reinforcement modified the resistance of specimen to penetration by about 3% over that obtained from increasing slab thickness 100%, See Fig. 13. Its noted that the disagreement between FE and experimental data decreased under this cartridge type. RHT model can simulate accurately the projectile erosion before excessive deformation which appears greatly in deformed projectile at low velocity.

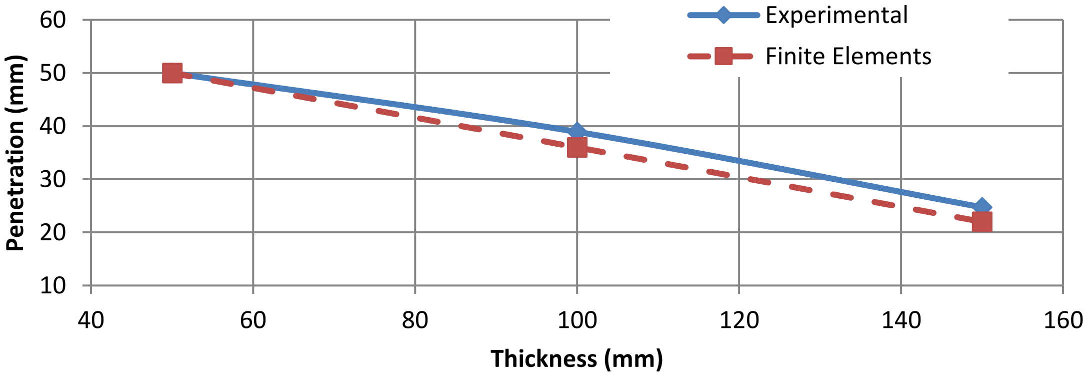

Fig. 13. Penetration-thickness curve for reinforced concrete specimens under 900 m/s velocity projectile

However, the disagreement noted between FE model and Experimental data, with respect to penetration value, may be attribute also to neglecting rotation and air resistance of High speed projectiles.

Generally, the results collected was in agreement with results obtained by Pavlovic et al. [23]. They concluded that the steel reinforcement addition did not enhance concrete strength against strike under Ruger rifle of

838 m/s projectile velocity after using external steel reinforcement mesh.

The small values of penetration in comparison to lectures was attributed mainly to using deformable projectiles which gives limited penetration when compared with rigid one. Zhang et al. [8] presented a linear relation between initial velocity and penetration for ogive nose projectile with muzzle velocity.

Irhan et al. [20] suggested that the penetration strength of a circular plain concrete slabs proportional to the thickness value and a linear relationship can be drawn for different slab thickness.

4.2 Crater size

4.2.1 Plain concrete specimens

Crater size can be defined as the diameter of concrete area spalled away due to projectile strike [24]. Fig. 14 shows the relation between specimen thickness and the crater size for experimental and FE data.

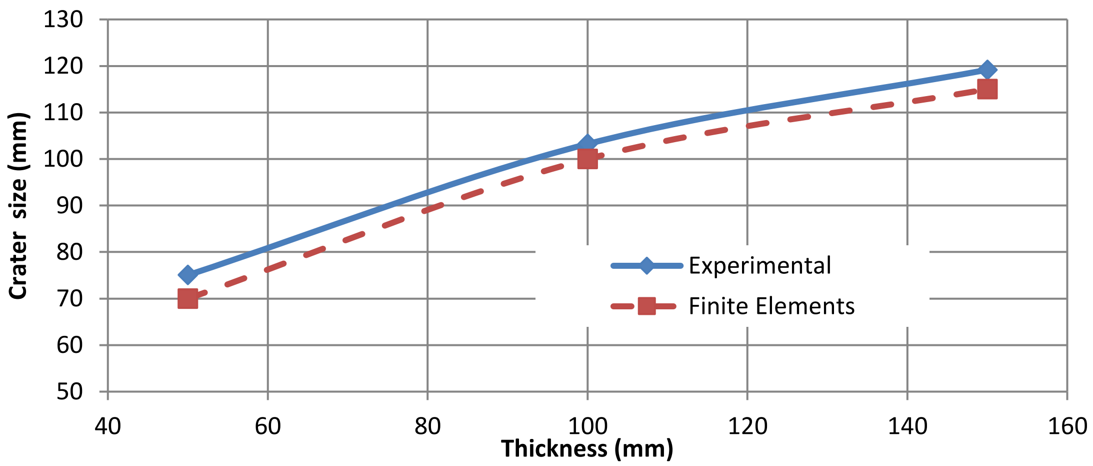

Fig. 14. Crater size-thickness curve for plain concrete specimens under 700 m/s velocity projectile

On the contrary to the penetration strength, crater size was increased with increasing slab thickness to record an increase of 38% when plain specimen thickness increased by 100%. Crater sizes value recorded for 150 mm plate was approximately near to the results recorded by Gomes & Shukla [25]. Zhang et al. [8] explained that using steel (rigid) projectiles recorded a greater values of crater size.

Generally, in comparison between penetration and crater values, it can be conducted that impact energy of the projectile dissipates greatly with penetrating resistance. Thus, the strain energy propagated within target surface spall it out and increase the crater size value.

Finite element data matched well with experimental data and the disagreement increased with slab thickness increase. Fig. 15 explains the comparison between experimental work and FE model for crater developed in 50 mm slab concrete. Effective plastic strain deformation criteria (*EPSF*) showed a great compatibility with erosion effect. This criteria, provided by ANSYS WB, defines the max. plastic strain developed in element when the element go to the permanent damage and failure beyond this limit. Thus a good results obtained from FE model.

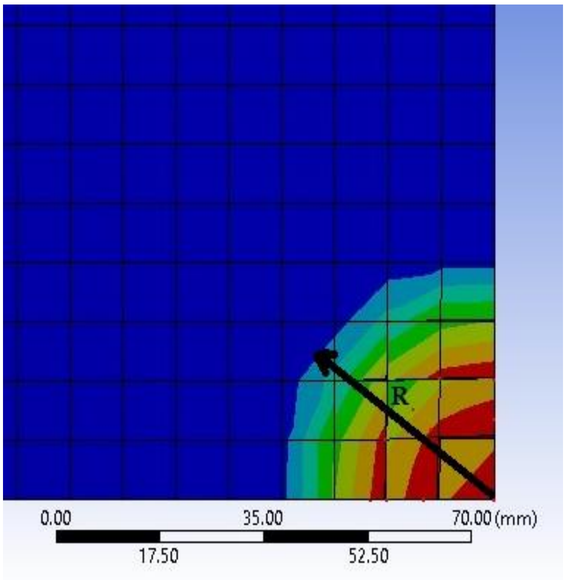

Fig. 15. Experimental and FE crater illustration

Increasing the projectile velocity resulted a greater crater value in comparison to that of low velocity due to great impact energy. See Fig. 16. As stated before, the low penetration value dissipates the residual energy within target surface and its proportional to the specimen thickness.

Finite element moves with experimental data in same trend with a disagreement value noted to be larger than 700 m/s projectile strike.

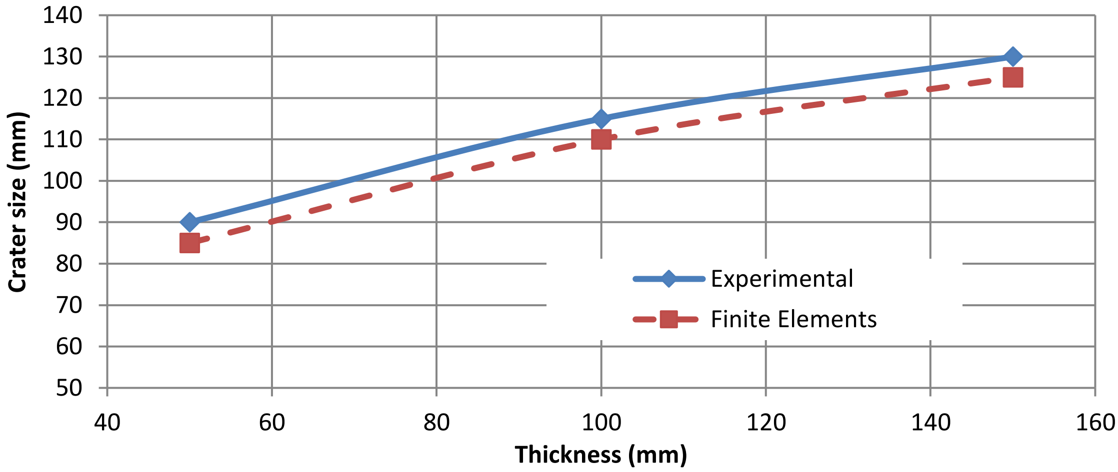

Fig. 16 Crater size-thickness curve for plain concrete specimens under 900 m/s velocity projectile

4.2.2 Reinforced specimens

The reinforcement decreased clearly the crater size of concrete target. Its noted that the crater size increased with increasing slab thickness due to increasing in concrete clear cover value. Steel reinforcement bars modified the consistency of concrete cover then improved the resistance to spalling of concrete on front and rear surfaces. Addition of steel reinforcement had clear effect on crater size, on contrast to penetration value. When the thickness of the specimens was 150 mm and projectile strike of 700 m/s, the reduction in the crater size was 43% after addition of steel reinforcement, as shown in Fig. 17

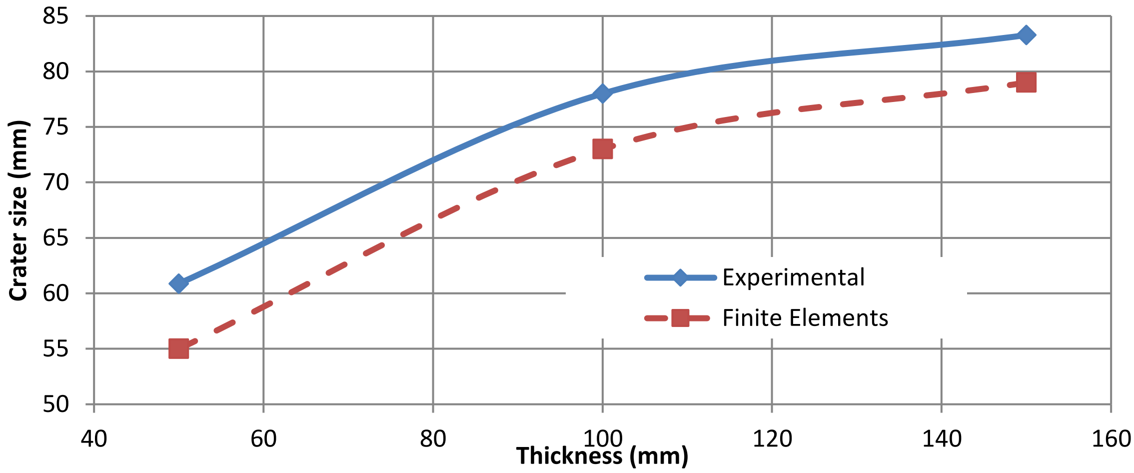

Fig. 17 Crater size-thickness curve for reinforced concrete specimens under 700 m/s velocity projectile

The increment in impact velocity was proportional to the crater values and the same trend was noted in general behavior for reinforced specimens as shown in Fig. 18. An improvement in crater strength was noted to be 35 % after adding steel reinforcement to the specimen of 150 mm thickness.

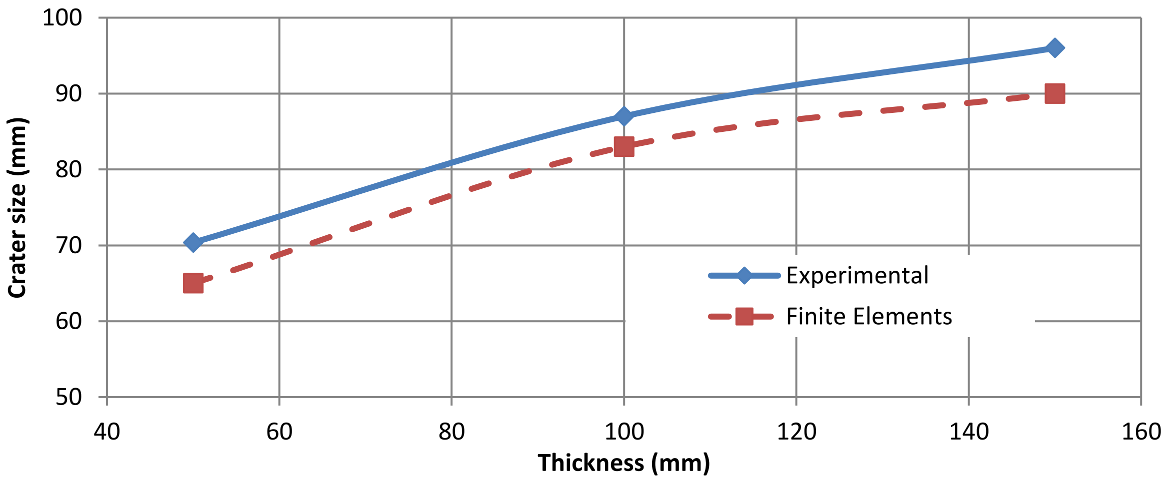

Fig. 18 Crater size-thickness curve for reinforced concrete specimens under 900 m/s velocity projectile

Numerical data showed clear disagreement but the general relation between crater-thickness-velocity carry same trend in comparison to the experimental data. The assumption of full interaction between concrete slab and steel reinforcement behind the mismatch between the numerical and experimental results. On the other hand, cracks propagation and gravel interlock modelling effect also on the model accuracy.

5. CONCLUSIONS

A relation between concrete slab characteristics and corresponding deformation due to most common rifle projectile drawn in the present study, in comparison to literature, It's concluded that:

- Penetration and crater resistance of plain concrete specimens enhanced by about 35%

and 37%, respectively at 100% slab thickness increment.

- Steel reinforcement modified the penetration and crater strength compared to plain specimens by 6% and 32%, respectively for 100 mm slab thickness.
- Penetration value draw a linear relationship with slab thickness while the crater value looks to be flatten at higher slab thickness.
- RHT material model provided by *ANSYS WB* align well with experimental data in simulating projectile impact on concrete.

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