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# Modelling Ballistic Impact of Firearm Projectiles on Compressed Earth Bricks

**Chung Han Lim**
Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400, Kota Kinabalu, Sabah, MALAYSIA.
E-Mail: andrew.lim@ums.edu.my; Tel: +6088-320000.

**ABSTRACT** In this study, the terminal ballistic behavior of firearm projectiles on compressed earth bricks (CEB) was simulated using finite element modelling. Bricks are very commonly used as cladding in buildings and compressed earth bricks have recently made a comeback as an environmentally friendly alternative to typical fired clay bricks. CEBs have proven to possess stronger strength, whilst requiring less energy to produce and emitting less $CO_2$ in the process. Whilst its mechanical properties are now well understood, there are very few studies that looked into the terminal effects of projectile impact onto brick faces and none at all on the ballistic impact on CEBs. Quite often, for buildings situated in conflict areas or war zones, brick clad walls are expected to provide resistance against ballistic impact of small arms fire. Ballistic testing of bricks can be difficult to carry out as it requires access to ammunition and gunnery range. In this study, CEB bricks are modelled in a finite element software ANSYS to simulate the terminal impact behavior of 9 mm caliber projectile. The results of this modelling were validated using another model where the CEB was replaced with a piece of European oak based on actual ballistic test results from a past journal paper that used the same material. By comparing the results of both ballistic simulation and actual ballistic experiment, the deviation between two results can be determined. The reference journal paper presents two numerical ballistic simulation on the penetration depth of European Oak and compressed earth brick subjected to impact by 9 mm bullets. The modelled penetration depth of European Oak subjected to impact by a 9 mm projectile at velocity of 412.7 m/s was 35 mm. Comparatively, the actual penetration depth of European Oak subjected to impact by the same projectile at the same travel speed was 46.5 mm. The deviation between simulated and actual penetration depth of the 9 mm projectile in the European Oak was 24.73%. The simulated penetration depth of compressed earth brick subjected to impact by a 9 mm projectile at velocity of 338.3 m/s was 17.34 mm. The deviation of 24.73% is considered quite high by comparing to other researcher's deviation therefore, more information such as exact dimension of the European Oak target and detailed material properties of European Oak and 9 mm bullet are needed to reduce the deviation gap.

**KEYWORDS:** Compressed earth bricks; ICEB; bricks; Terminal ballistics; Finite element modelling; Projectile impact.
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## INTRODUCTION

Brick is one of the most common materials used in the construction industry. It is used to make walls and wearing course of pavement in masonry construction. Brick has advantages of low thermal conductivity and low cost. But conventional bricks have relatively low compressive and tensile strength, which makes it impractical for structural load-bearing purposes. To make the bricks useful, practical material in structural load-bearing purpose, compressed earth bricks (CEB) are introduced. The CEB, which originated in the mid-twentieth century, represents a technological innovation among the raw earth techniques such as rammed earth, adobe, and cob (Walker, 1995). CEBs are a relatively new form of earth masonry units that combine local soil, stabilizer, and water under pressure to form an earth brick (Sitton *et al.*, 2018). By using soil, a readily abundant resource nearly everywhere in the world, as the main component in block production, CEBs offer a sustainable alternative to traditional masonry units (Bredenoord, 2017). In the past, CEB production involves compressing a mix of soil, sand and water into a rectangular shape and the usage of these bricks normally is for wall construction (Rigassi, 1985). Several possible building systems can be used by CEB, which are loadbearing and reinforced masonry, infill masonry, and special applications like facing floors and walls, decoration, claustra work, and interlocking building system. In the modern CEB production process, normally, a chemical binder such as Portland cement and lime are added for improving the compressive strength of the bricks, the bricks then called as compressed stabilised earth bricks (CSEB). Compressed earth brick (CEB) is using in constructing load bearing wall due to its high compressive strength and tensile strength. The raw materials of CEB include soil, sand, and Portland cement. The CEB is manufactured by compressing after all of the raw materials are filling in a mould.

To date, no form of any ballistic testing has been done on CEBs to assess its behaviour under impact loading. Therefore, for the purposes of this study, ballistic resistance of CEBs is investigated using finite element simulation on computers. An experiment of shooting test on different flat wood targets, namely Douglas fir, European Pine, European Oak, Merbau, Bangkirai, and Azobe using three different types of 9 mm ammunition such as the standard ball, Action NP, Ball Subsonic and hollow point rounds has been carried out (Koene & Broekhuis, 2017). For the European Oak target, the projectile that has the highest penetration depth is 9 mm ball while the projectile that has the lowest penetration depth is 9 mm Action NP.

The objectives of this study are to determine and justify the simulated penetration depth of 9 mm projectile in CEB target filled with cement mortar. In order to justify the simulated penetration depth of the 9 mm projectile in the CEB target, another ballistic testing is simulated based on other past research which done by other researcher. The results deviation of simulated and actual ballistic testing is calculated. The calculated result deviation is used to justify the simulated penetration depth of the 9 mm projectile in the CEB target.

## BACKGROUND THEORY

To date, no research has been done on ballistic testing of compressed earth brick (CEB) and compressed stabilized earth brick (CSEB). However, the research done by (Maho *et al.*, 2019) using 9 mm rounds on to assess energy absorption and failure modes of different materials found that typically the terminal ballistic behavior of particle impact can vary between a) perforation, b) spalling, c) penetration and d) ricocheting as shown in Figure 1.

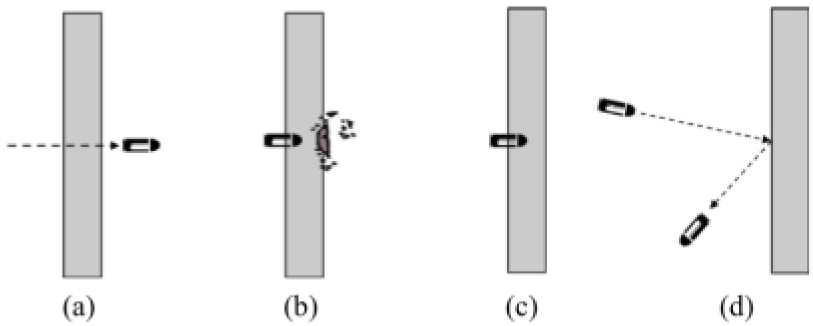


**Figure 1.** Typical modes of terminal behavior of particle impact – a) perforation, b) spalling, c) penetration and d) ricocheting (Maho *et al.*, 2017).

(Sukontasukkul *et al.*, 2013) had done a study related to the ability of rubberized concrete (RC) for improving the impact performance of steel fiber reinforced concrete (SFRC) bulletproof panel which was subjected to direct bullet impact. The rubber replacement level for fine aggregate at 50%, 75%, and 100% by volume fractions were used to substitute portions of the thickness of the SFRC panel. Soft layer (RC) acted as impact absorbing layer to absorb parts of the energy due to the bullet and allow less impact to reach the hard layer (SFRC).

Presently, no research has been done on ballistic simulation of compressed earth brick (CEB) and compressed stabilized earth brick (CSEB). To obtain the information of ballistic simulation on CEB and CSEB, research which is related to the ballistic simulation on any structural material has become the reference material. In the research done by (Pundhir *et al.*, 2019), ballistic impact simulation of various thickness composite plate which consisted of Ultra high molecular weight polyethylene (UHMWPE) and alumina was performed by using ANSYS-AUTOYN 16.0.

## METHODOLOGY

*Ballistic Simulation of European Oak Target Subjected to Impact by a 9 mm Projectile*

The conditions of this ballistic simulation are based on ballistic testing research previously carried out (Koene & Broekhuis, 2017). The type of material and projectile that has been chosen for the ballistic simulation in this thesis are European Oak and 9 mm Action NP projectile. The dimension of 9 mm Action NP projectile is 9 mm diameter with 10.54 mm length. The dimension of the wooden target is in rectangular shape with 200 x 200 x 60 mm. The ballistic simulation was done by using the explicit dynamic command in ANSYS software. The material of the projectile in the ballistic simulation is lead. The material properties of European Oak and lead are referred to past research (Steinberg, 1996).

The procedures of the ballistic simulation of 9 mm Action NP projectile on European Oak are consisted of several steps. First, the explicit dynamic command was selected in ANSYS workbench. Next, the materials of Oak Hardwood and lead material were selected as engineering data for assigning to the selected geometry model. Then, the modelling of the projectile and European Oak geometry according to the specific dimension mentioned previously was done by using the Design Modeler software in ANSYS. The ballistic simulation set-up is shown in Figure 2.

After the geometries of the material were modelled, the several parameters were assigned to the models such as meshing size, impact velocity of projectile on the European Oak, duration and time step safety factor of ballistic simulation. The European oak target was modelled as a solid with 5 mm mesh size, and velocity of the projectile was 338.3 m/s as summarized in Table 1.

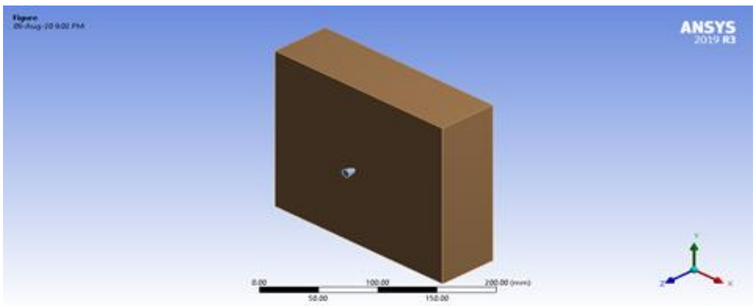


**Figure 2.** Finite element model of the European oak subjected to ballistic.

**Table 1.** Summary of the parameters used in the ballistic simulation of CEB.

| Parameter | Description |
|---|---|
| Mesh size | 5 mm |
| Velocity of projectile | 412.7 m/s |
| End time | 0.0005 seconds |

After the ballistic simulation is done, comparison between the penetration depth in simulation and penetration depth from real experiment date will be done as well. The deviation in percentage between this two penetration depth data is calculated by difference of actual and simulated penetration depth divided by actual penetration depth and multiply by 100 %.

*Ballistic Simulation of CEB Subjected to Impact by a 9 mm Projectile*

The dimension of projectile in this ballistic simulation is 9 mm diameter with 10.5 mm length. The dimension of CEB target is 250 x 125 x 100 mm (Length x Width x Height). The simulation models three types of material including its properties, namely the CEB (Elahi *et al.*, 2020) and its cement mortar infill as well as lead projectile.

The procedures in ballistic simulation of CEB are same as ballistic simulation of European Oak target. The only differences are panel material and projectile speed. The ballistic simulation setup of CEB is shown in Figure 3. As with the European Oak target, the CEB target was modelled as a solid with 5 mm mesh size, and velocity of the projectile was 338.3 m/s as well. This is summarized in Table 2.

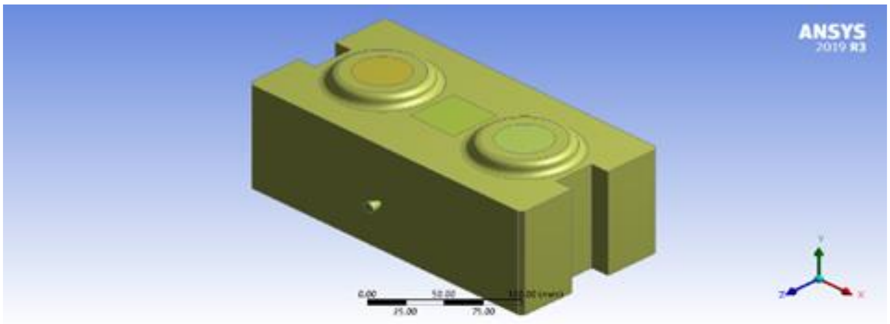


**Figure 3.** Finite element model of the CEB subjected to ballistic impact.

**Table 2.** Summary of the parameters used in the ballistic simulation of CEB.

| Parameter | Description |
|---|---|
| Mesh size | 5 mm |
| Velocity of projectile | 338.3 m/s |
| End time | 0.0005 seconds |

After the ballistic simulation of CEB in ANSYS software was performed. The penetration depth of 9 mm projectile on the CEB target was determined and justified based on the possible differences between the parameters in the ballistic simulation and real life and calculated deviation from the ballistic simulation of European Oak.

## RESULT AND DISCUSSION

*Result of Ballistic Simulation of European Oak Target Using 9 Mm Action NP Projectile*

After the 9 mm Action NP projectile hit the European Oak target, the type of damage of the European Oak panel subjected to high speed impact is penetration. The penetration depth of the projectile into the European Oak target is 35 mm. The penetration conditions of the projectile at t = 0.0005 s is shown in Figure 4 and Figure 5. The penetration depth of the projectile in the European Oak target can be obtained by observing the number of meshing cube in Figure 3 and z-axis position tracing of the projectile in the European Oak target. The position tracing line of the projectile is shown in Figure 4. The penetration depth can be obtained by calculating the number of the meshing cube touched by the tracing line in Figure 4. Each dimension of the meshing cube is 5 x 5 x 5 mm (length x width x height). Total of 7 meshing cube are touched by the position tracing line of the projectile. Therefore, the penetration depth of the projectile in European Oak is 35 mm.

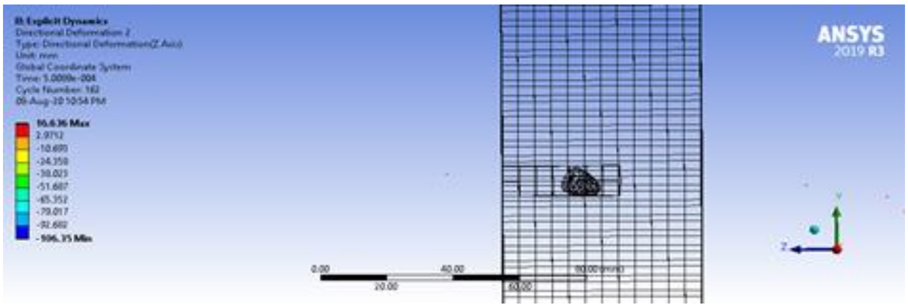


**Figure 4.** Cross-section view showing penetration of 9 mm round in the European Oak.

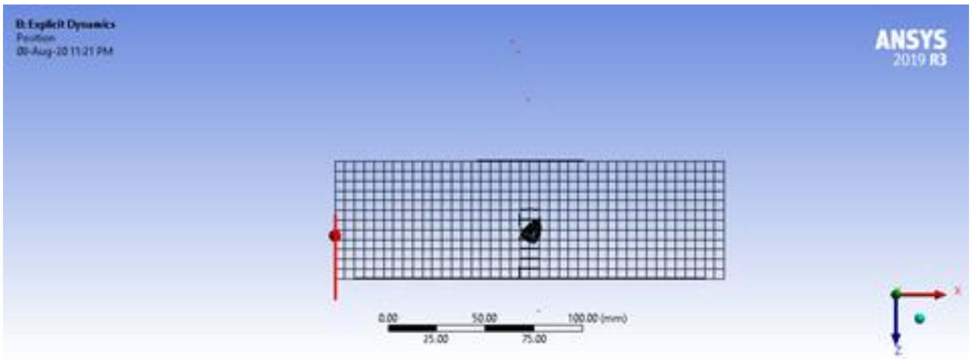


**Figure 5.** Plan view showing penetration of 9 mm round in the European Oak.

The penetration depth of 9 mm Action NP projectile on the European Oak target in the referred journal article is 46.5 mm. The penetration depth deviation between ballistic simulation and real-life testing is 24.7%.

*Justification of Simulation Accuracy*

In order to determine the penetration depth deviation of 9 mm projectile in the European Oak target was acceptable or not, a comparing of the calculated deviation with other researcher's results was needed. The deviations in the past research are lower 17%. The deviation of penetration depth of 9 mm Action NP projectile in the European Oak target between ballistic simulation and experiment is 24.7% which is quite high by comparing with the other researcher's results. The high percentage of deviation is caused by some limitations in this study.

*Assessment of the Moisture Content of European Oak Target in Ballistic Testing and Simulation*

According to Koene & Broekhuis, 2017, the average moisture content of European Oak target during ballistic testing is 37.1 % which is the highest moisture content between the different types of wood that had been tested in the experiment. This can cause the European Oak target to expand and reduced the physical strength of the European Oak target. On the other hand, the parameter of moisture content of the materials was not covered or considered during ballistic simulation in ANSYS software. The differences of European Oak target moisture content in ballistic testing and ballistic simulation can cause deviation between ballistic performance of European Oak target against the high-speed impact from 9 mm projectile in ballistic testing and simulation.

*Effect of Meshing Size on the European Oak Target and 9 mm Projectile Models*

The relationship between the meshing size of simulated models and accuracy of the simulated models against real objects is inverse. The lower the meshing size of the simulated models, the higher the accuracy of the simulated models against real objects.

The range of the meshing size of the target and projectile models in the past research is from 0.3 mm to 1 mm. On the other hand, the meshing size of the simulated European Oak target and 9 mm projectile in the ANSYS software is 5 mm. This is at least 5 times of the meshing sizes of the simulated models in the past research which done in another research. This may cause a reduction in the accuracy of simulated models against real objects.

*Comparison - Material Properties of the European Oak Target and 9 mm*

Only a few physical properties of European Oak target are provided in the referred journal article such as average density, average moisture content, ultimate tensile strength, shear strength and Jangka hardness. Other physical properties of the European Oak than the list of properties mentioned in previous sentence such as Young's modulus, Poisson's ratio, bulk modulus, and shear modulus are default value in the ANSYS software. Other than that, all of the properties of lead are also default value in the ANSYS software.

Although the default values of the properties of the materials are referred to (Steinberg, 1996); and Granta Design. The default properties in the ANSYS software will not reflect exactly as the real properties of the materials during ballistic testing. This will affect the ballistic performance of the simulated materials such as European Oak and lead which caused deviation in ballistic performance of the simulated materials between ballistic testing and simulation.

*Dimensions of the European Oak Target*

Since the exact dimension of the European Oak target used in the ballistic testing is not mentioned in the research which done by (Koene & Broekhuis, 2017). Therefore, the dimension of European Oak target model in ANSYS, 200 x 200 x 60 mm is an assumption based on other researcher's study. Because the dimension is an assumption, there must be differences against the dimension of real European Oak target in the ballistic testing. The dimension of European Oak target can affect the penetration depth of the projectile. For proving this, another two ballistic simulation of European Oak target with different dimensions are performed. The dimensions of European Oak target included 100 x 100 x 60 mm and 100 x 100 x 100 mm. During the three ballistic simulations, the parameters other than dimension of European Oak target were kept constant.

The penetration depth of 9 mm projectile in the 200 x 200 x 60 mm European Oak target was 35 mm. On the other hand, the penetration depth of 9 mm projectile in the 100 x 100 x 60 mm European Oak target is 30 mm. The penetration depth of 9 mm projectile in the 100 x 100 x 100 mm European Oak target is 40 mm. From the results of the ballistic simulations, the penetration resistance of European Oak target is increased when the dimension of European Oak target is decreased. Furthermore, the penetration resistance of European Oak target is decreased when the thickness of European Oak is increased.

In short, the three ballistic simulations have proved that the dimensions of European Oak target can affect the penetration depth of 9 mm projectile. Therefore, the deviation of penetration depth in ballistic simulation and ballistic testing can be caused by differences between the dimensions of European Oak target in ballistic simulation and testing.

*Result of Ballistic Simulation of CEB using 9 mm Projectile*

After the 9 mm projectile hit the CEB target, the type of damage of the CEB subjected to high speed impact is penetration. The penetration depth of the projectile into the CEB is 17.3 mm. The penetration conditions of the projectile at t = 0.0005 s is shown in Figure 6.

The penetration depth of 9 mm projectile in CEB is obtained by referring Figure 6(a) and Figure 6(b). The length of the red line shown in Figure 6 is represented as the penetration depth of 9 mm projectile in CEB which is the sum of 3 base of triangle meshing unit and 3 mm. The length of each base of triangle meshing unit is 4.8 mm. Therefore, the sum of the values is 17.34 m. Based on the deviation of 24.73 % found in the ballistic simulation of 9 mm Action NP projectile in the European Oak target, the real penetration depth should be 17.3 ± 4.2 mm.

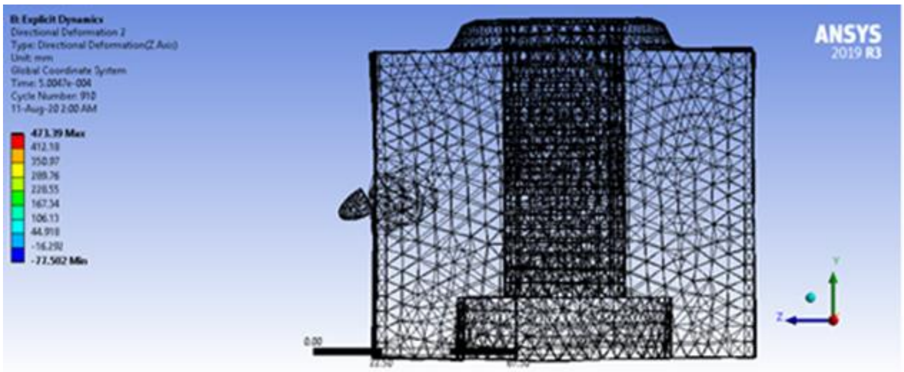


**Figure 6.** Plan view showing penetration of 9 mm round in the CEB.

*Discussion on the Penetration Depth of 9 mm Projectile on the CEBs*

The deviation of 9 mm Action NP projectile penetration depth in the European Oak target between ballistic simulation and experiment was 24.7 %. Based on the calculated deviation percentage, deviation of the simulated penetration depth of 9 mm projectile in compressed earth brick CEB) filled with mortar should be approximately the same as 24.7 %.

The high percentage deviation of the simulated penetration depth of 9 mm projectile in CEB filled with mortar will decrease the accuracy of the predicted penetration depth of 9 mm projectile against real penetration depth of 9 m projectile. The deviation is caused by several limitations that are involved in the ballistic simulation of 9 mm projectile on the CEB.

*Modelling Projectile Lead in the Simulation*

The properties of assigned material for the 9 mm projectile model in the ballistic simulation on the CEB filled with cement mortar target, lead is default properties in ANSYS software. Although the default values of the properties of the lead in ANSYS software are referred to (Steinberg, 1996). The default properties of materials in ANSYS software still can't guarantee is exactly same as the properties in real life. The ballistic performance of the 9 mm projectile can be affected due to difference material properties in simulation and actual condition. The material properties differences of lead between simulation and actual condition are due to inaccessibility of data associated to the real dimension of European Oak target from the referred journal article.

*Moisture Content of the CEB*

The major composition of CEB is consist of sand and clay. The physical properties of sand and clay such as density, shear strength, and compressibility are affected by moisture content. Therefore, the properties of CEB will be affected by moisture content also. In addition, the ANSYS software can't assign a moisture content parameter to the CEB model in a ballistic simulation. On the other hand, the moisture content of CEB in real life is existed and is always subjected to change due to the temperature and relative humidity of the atmosphere surrounding it.

The difference between the moisture content of the CEB in simulation and actual condition will cause some deviations on the penetration depth of 9 mm projectile in ballistic simulation and experiment. The moisture content limitation is due to the incapability of ANSYS software to take account the moisture content parameter in the simulated models through ballistic simulation.

*Impact Velocities of the 9 mm Projectile on the CEB*

The impact velocity of the 9 mm projectile on the CEB filled with cement mortar in simulation is 338.3 m/s. This velocity is obtained from the ballistic specification of American Eagle Handgun 9mm bullet. The possible factor that may cause differences impact velocity of the 9 mm projectile on the CEB target in real life experiment is the wind speed of the ballistic testing place. This is because the wind speed and condition (indoor or outdoor) of ballistic testing place for American Eagle Handgun 9mm bullet are the unknown parameters. Therefore, the difference between the impact velocity of the 9 mm projectile on the CEB target in simulation and actual condition will be occurred and this will also cause deviation in the penetration depth of 9 mm projectile on the CEB in ballistic simulation and experiment.

*Meshing Size of CEB, Cement Mortar and 9 mm Projectile Models*

The meshing size assigned to the CEB, the cement mortar and the 9 mm projectile models is 5 mm. As mentioned earlier, the meshing size of a simulated model is relating to the accuracy of the model against the actual condition. The relationship between the meshing size and accuracy is inverse. The smaller the size of meshing in a model, the higher the accuracy of the model against actual condition.

The range of meshing sizes of the past research are from 0.3 mm to 1 mm. The meshing of size of 5 mm in the ballistic simulation of 9 mm projectile on the CEB target is much bigger than the meshing sizes of past research which causes deviation in the penetration depth of 9 mm projectile on the CEB in ballistic simulation and experiment. The limitation of meshing sizes of CEB, cement mortar and 9 mm projectile model is because lower capacity of laptop RAM unable to support huge RAM requirement by the ANSYS software.

## CONCLUSION

This study first presented the ballistic simulation of 9 mm Action NP projectile on European Oak target. A penetration depth of 35 mm was found for the 9 mm Action NP projectile model in the European Oak target model. On the other hand, the penetration depth 46.5 mm was found in the ballistic experiment for the 9 mm Action NP projectile in the European Oak target from the referred journal article. The calculated deviation between two penetration depths of 9 mm projectile in ballistic simulation and experiment was 24.7 %.

Furthermore, this study has also presented a ballistic simulation of 9 mm projectile on CEB filled with cement mortar target. A penetration depth of 17.3 mm was obtained for the 9 mm projectile in the CEB filled with cement mortar target. Based on the deviation of 24.7 % found in ballistic simulation of European Oak, the actual penetration depth of 9 mm projectile in the CEB target is 17.3 ± 4.2 mm.

The results presented in this study can be referred by researcher who is interesting to conduct a further study on the ballistic testing and ballistic simulation of compressed earth brick.

## ACKNOWLEDGEMENTS

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