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Assessing Expected Fractional Damage of Above-ground Buildings from Air-to-surface Weapons based on Indirect Fire Concept

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ABSTRACT

For the expected fractional damage of building targets from air-to-surface weapons, the US has used the JMEM/AS method, which is based on the direct-fire concept. However, the damage redistribution assumption in the direct-fire concept could induce serious errors in damage estimation of building targets. In this paper, a method for the expected fractional damage of building targets is proposed based on the indirect-fire concept. From the proposed model, it is shown that the joint munitions effectiveness manuals/air-to-surface (JMEM/AS) method is not appropriate for building targets, especially for attacks with multiple aiming points. It is recommended that the indirect-fire concept should be adopted for weaponeering even for air-to-surface weapons.

Keywords: Weaponeering, air-to-surface, joint munitions effectiveness manuals, expected fractional damage, air-to-surface weapons

1. INTRODUCTION

The main purpose of weapon system is to achieve a required level of damage to a given target. Since there are various weapon types and operation methods, it is important to determine which weapon among the available weapons is the most effective for the mission and how to operate it. Weaponeering is this decision-making process by estimating and comparing the quantities of different weapons required for the desired level of damage. For weaponeering, two major inputs are required: weapon delivery accuracy and the effectiveness index (EI). Weapon delivery accuracy is a statistic measure of capability to place a weapon system on an intended point, which includes human performance factors, aiming error, and ballistic dispersion. Effectiveness index is a numerical value that represents the amount of a given degree of damage level, and has different values depending on target, weapon system, and damage level.

For above-ground buildings, building mean area of effectiveness (MAE_{bldg}) is adopted as the EI type. MAE_{bldg} is the circular- or rectangular-shaped area with the origin as impact point of the weapon within which building components (e.g., slab and wall) suffer structural damage. Although numerical values of MAE_{bldg} for air-to-surface weapons can be obtained from the Joint Munitions Effectiveness Manual Air-to-surface Weaponeering system (JAWS)[1], which is maintained by the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME), US, those data are classified as high security. With given delivery errors and MAE_{bldg}, the damage to a building target can be estimated by the Windows version of Joint Munitions Effectiveness Manuals (WINJMEM), which is the Window-based program for the damage calculation. When JAWS is not available, MAE_{bldg} can be determined analytically from following procedures:

- Blast load calculation,
- Damage assessment of local structural components, such as columns and girders,
- Damage assessment from progressive collapse.

Pressure history from detonation can be simply calculated when explosive amount is given[2]. However, it should be noted that weight of explosive in a warhead cannot be used directly for blast load calculation. Since most warheads consist of explosive and covering case, part of energy from explosion should be consumed to break up covering case and accelerate resulted fragments. This casing effect can be considered by various empirical or analytical methods[3-7]. With estimated blast loads, local damages of critical structural components can be assessed by pressure-impulse(P-I) diagrams[8-10]. P-I diagrams represent combinations of peak pressure and impulse, which cause a predetermined level of structural response[11]. P-I diagrams can be prepared by numerical analysis, such as finite element method and single-degree of freedom model[12-19]. Once local damage is assessed, damage from progressive collapse should be considered. When local structural components fail, the damaged building structure should seek alternative load paths to withstand the remaining loads. As a result, additional structural component failures can occur[20-23]. Based on this procedure, the global damage of building from warhead explosion can be analysed, of which average value can be considered as MAE_{bldg}

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To calculate the damage from air-to-surface weapons, WINJMEM uses the open-end method based on the direct-fire[24]. The basic concept of the direct-fire is that the damaged target elements in an area target are redistributed uniformly within the total target area after each attack. This concept could be an appropriate approach when the area target consists of multiple individual targets, and surviving targets line up uniformly within the target area after an attack. However, it does not seem to be appropriate to assume that the damaged portion of a building moves or damage is redistributed within a building area. Thus, the indirect-fire concept should be adopted for building targets, even if air-to-surface weapons are used. The indirect-fire concept, which is used generally for surface-to-surface weapons, does not allow redistribution of damaged portions to the whole target area. In this paper, a new damage calculation method based on the indirect-fire concept is proposed for air-to-surface weapons, and the expected fractional damages from the new method and traditional JMEM/AS method are compared.

2. JMEM/AS METHOD FOR ABOVE-GROUND BUILDING TARGETS

Here, the JMEM/AS weaponeering method for above-ground building targets is reviewed based on Morris Driel's book[25], which is currently being used by US Military Forces. The basic concept of weaponeering is to calculate expected damage to a given target from a specific weapon system by accounting for delivery accuracy and lethality of the weapon. To account for the lethality of the weapon on building targets, a rectangular-shaped MAE_{bldg} is used, which can be represented by effective target length L_{ET} and width W_{ET}:

$$L_{ET} = \sqrt{MAE_{bldg}}, \qquad W_{ET} = W_A + \sqrt{MAE_{bldg}} - L_A$$

$$\text{when } \sqrt{MAE_{bldg}} > L_A \tag{1}$$

$$L_{ET} = L_A,\; W_{ET} = W_A,\; \text{ when } \sqrt{MAE_{bldg}} \le L_A \tag{2}$$

where, W_A is target width, and L_A is target length.

For mathematical simplification [(Eqn. (6)] in combining lethality and delivery accuracy, the effective lengths should always be larger than target dimensions (length and width). Thus, when one of the target dimensions is larger than the lethal area, the size of the lethal area is enlarged and the damage probability inside the lethal area is reduced. This is done by adopting the following effective pattern dimensions:

$$L_{EP} = \max\left(L_{ET}, L_A\right) \tag{3}$$

$$W_{EP} = \max\left(W_{ET}, W_A\right) \tag{4}$$

$$P_{CD} = \frac{L_{ET}W_{ET}}{L_{EP}W_{EP}} \tag{5}$$

where, L_{EP} and W_{EP} are effective pattern length and width, respectively, which represent the dimensions of the enlarged lethal area, and P_{CD} is the damage probability inside the lethal area.

The expected fractional damage can be given by:

$$EFD = E(F_R)E(F_D)P_{CD}C_R \tag{6}$$

where, C_R is reliability, $E\left(F_R\right)$ and $E\left(F_D\right)$ are expected damage in range and deflection directions, respectively. The range direction expected damage can be given by:

$$E(F_R) = \int_{-\infty}^{+\infty} F_R(x)g_R(x)dx \tag{7}$$

where $g_R(x)$ is probability that the weapon hits at x, representing delivery error in range direction and can be assumed as following normal distribution function:

$$g_R(x) = \frac{1}{\sigma_R\sqrt{2\pi}}\exp\left[\frac{-x^2}{2\sigma_R^2}\right] \tag{8}$$

where, σ_R is standard deviation in range direction.

In Eqn. (7), $F_R(x)$ is the area ratio of the overlapping area between target and lethal areas to the target area when the weapon detonates at x, and can be given by:

$$F_R(x) = \begin{cases} 1 & \text{when } -t < x < t \\ \dfrac{L_{EP}+L_A}{2L_A} + \dfrac{x}{L_A} & \text{when } -s \le x \le -t \\ \dfrac{L_{EP}+L_A}{2L_A} - \dfrac{x}{L_A} & \text{when } t \le x \le s \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

where $s = \dfrac{L_{EP}+L_A}{2}$, and $t = \dfrac{L_{EP}-L_A}{2}$

Thus, the expected fractional damage can be determined by Eqn. (6).

3. PROPOSED METHOD FOR ASSESSING THE DAMAGE TO GROUND BUILDING TARGETS

JMEM/AS adopted the methodology for area targets directly to building target cases. This is based on the direct-fire method, which can be represented by uniform redistribution of all surviving target elements within the target area after a single attack. This direct-fire concept has been adopted for all air-to-surface weapons regardless target types in JMEM/AS. However, when a building is damaged by a single attack, the damaged area can not be redistributed. Thus, the indirect-fire concept, which does not allow the damage redistribution, should be adopted for building targets, even if the weapon is air-to-surface type. A new damage calculation method for building targets is proposed based on this indirect-fire concept.

Figure 1 shows building target area and delivery grids. The total grid size can be determined by target size and MAE_{bldg}. When the shortest distance between the target edge and detonation point is longer than lethal radius R_{lethal}, which is $\sqrt{MAE_{bldg}/\pi}$, there is no damage to the target. Thus, the grids only within target edge plus R_{lethal} need

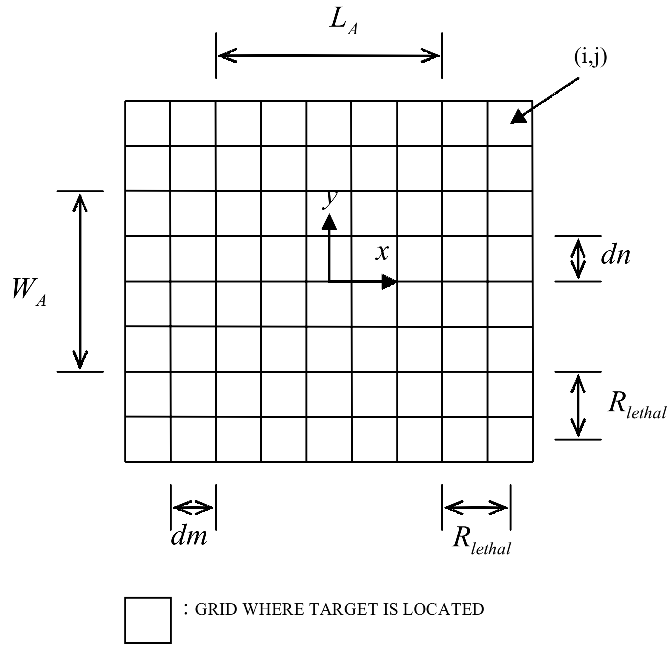


Figure 1. Delivery grids and target area.

to be considered, as shown in Fig. 1. The probability that the weapon hits within cell (i, j), $I(i, j)$ can be given by:

$$I(i,j)=\int_{X_{(i,j)}-dm/2}^{X_{(i,j)}+dm/2}\int_{Y_{(i,j)}-dn/2}^{Y_{(i,j)}+dn/2}\frac{1}{2\pi\sigma_R\sigma_D}\exp\left[-\frac{(x-\mu_R)^2}{2\sigma_R^2}-\frac{(y-\mu_D)^2}{2\sigma_D^2}\right]dydx \tag{10}$$

where, $X_{(i,j)}$ is the x-coordinate of cell (i, j), $Y_{(i,j)}$ is the y-coordinate of cell (i, j), dm is the x-direction (or range direction) size of the cell, dn is the y-direction (or deflection direction) size of the cell, σ_R and σ_D are standard deviations in range and deflection directions, respectively, μ_R and μ_D are the range and deflection coordinates of aiming point, respectively.

Then, the damage probability of cell (i,j) can be given by:

$$S(i,j)=\sum_{k=1}^{m}\sum_{l=1}^{n}\left(C_R*I(k,l)*D(k,l,i,j)\right) \tag{11}$$

where, m and n are the total number of cells in range and deflection directions, respectively, and D is:

$$D(k,l,i,j)=\begin{cases}1 & \text{if } (X_{(k,l)}-X_{(i,j)})^2+(Y_{(k,l)}-Y_{(i,j)})^2<R_{lethal}{}^2\\ 0 & \text{elsewhere}\end{cases} \tag{12}$$

where, $X_{(k,l)}$ and $Y_{(k,l)}$ are x and y locations of cell (k, l), respectively.

When the number of weapons is N_{weapon} with a constant aiming point, the expected fractional damage EFD can be given by:

$$EFD=\frac{\sum_{i,j\in A_{target}}1-(1-S(i,j))^{N_{weapon}}}{N_{target}}*100(\%) \tag{13}$$

where, A_{target} represents (i, j) in which cell target is located, N_{target} is total number of grids overlapping with target area.

When $N_{weapon1}$ and $N_{weapon2}$ are used at two different aiming points (μ_{x1},μ_{y1}) and (μ_{x2},μ_{y2}), respectively, the expected fractional damage can be calculated by:

$$EFD=\frac{\sum_{i,j\in A_{target}}1-(1-S_1(i,j))^{N_{weapon1}}(1-S_2(i,j))^{N_{weapon2}}}{N_{target}}*100(\%) \tag{14}$$

where, S_1 and S_2 are damage probabilities of cells calculated from Eqns (10) and (11) by adopting aiming points (μ_{x1},μ_{y1}) and (μ_{x2},μ_{y2}), respectively.

4. COMPARISON OF EXPECTED FRACTIONAL DAMAGES FROM JMEM/AS AND THE PROPOSED METHOD

Expected fractional damages were calculated in various situations to check the amount of error from the redistribution concept of the JMEM/AS method by comparing results from the proposed method. For the proposed method, a computer program using MATLAB[26] was prepared.

4.1 Single Aiming Case

With a fixed aiming point at the centre of a target, which is a 50 m × 50 m square building, the expected fractional damages at different attack numbers were calculated, as shown in Figs 2, 3, and 4. Weapons with 100 m^2, 500 m^2, and 1000 m^2 as MAE_{bldg}, and 5 m, 10 m, and 15 m as circular error probabilities (CEPs), were considered. In these cases, it was shown that the JMEM/AS method underestimates the expected fractional damage by a maximum of 29 per cent and overestimates by a maximum of 35 per cent compared to the results from the proposed method. The main purpose of weaponeering is to choose the most effective weapon system for a given target. Thus, the calculated expected fractional damage should be at least either conservative or non-conservative to compare the effectiveness of various weapons, even if the calculated values are not very accurate.

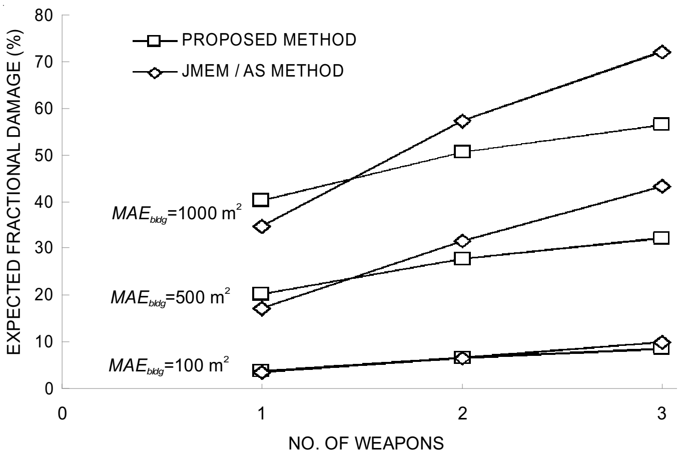


Figure 2. Expected fractional damage when CEP is 5 m.

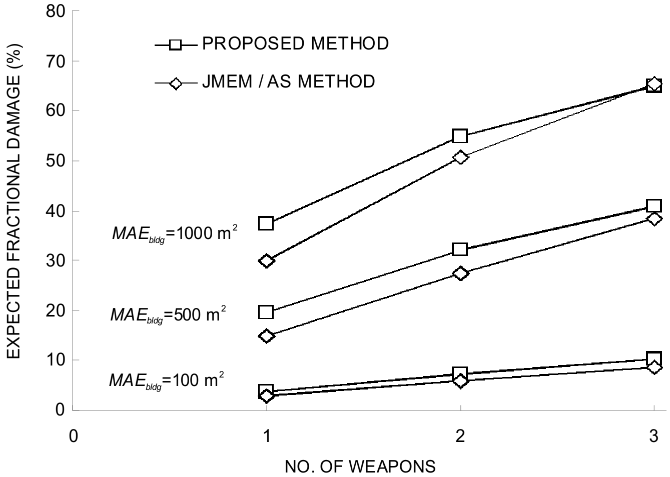


Figure 3. Expected fractional damage when CEP is 10 m.

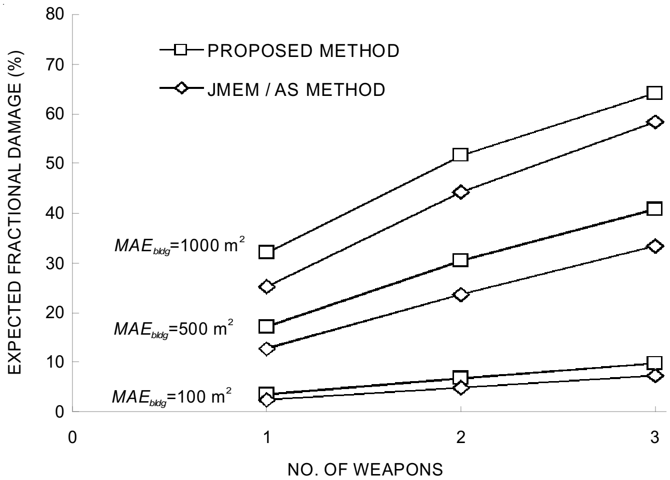


Figure 4. Expected fractional damage when CEP is 15 m.

Thus, it can be said that the JMEM/AS method is not appropriate for weaponeering on building targets with a single aiming point since it could induce both conservative and non-conservative expected fractional damages.

4.2 Multiple Aiming Case

When a target is not square, as shown in Fig. 5, using more than one aiming point could be more efficient rather than adopting one aiming point. The expected fractional damages from a total of two weapons (one for each aiming point) with 1000 m^2 and 2000 m^2 as MAE_{bldg} were calculated based on the JMEM/AS and the proposed method, as shown in Figs. 6 and 7. In these cases, four different CEPs (1 m, 5 m, 10 m, and 15 m) were considered.

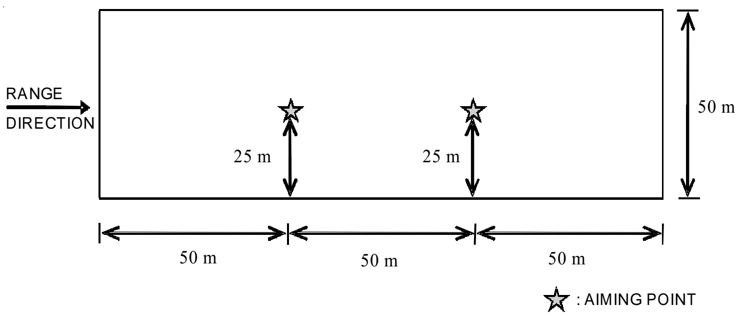


Figure 5. Two aiming points.

The redistribution of the damage in the JMEM/AS induces 23-29 per cent more in the expected fractional damages compared to those from the proposed model. The results from 1m CEP case can be used for validation of the proposed method. 1m CEP represents that there is almost no delivery error compared to the target size. For 1000 m^2 MAE_{bldg} and no delivery error, the solution for the expected fractional damage is $[\{2\times1000\ m^2/(150\ m\times50\ m)\}\times 100]$per cent $\approx$ 26.7 per cent, which shows only 0.3 per cent difference with the result from the proposed model (Fig. 6). This 0.3 per cent difference may come from the 1m CEP or the cell size. Fig. 8 shows the comparison of calculated damage from the JMEM/AS and the proposed method when MAE_{bldg} is 1000 m^2 and CEP is 15 m. It can be shown that the proposed method can show the different damage probabilities depending on location, although the JMEM/AS shows the constant damage within the building area.

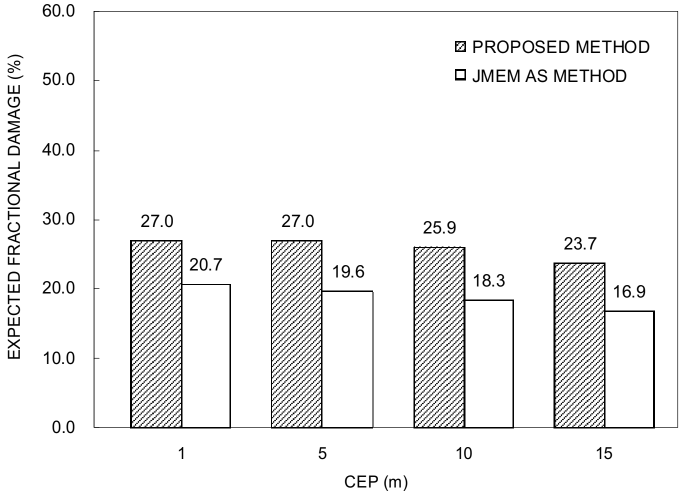


Figure 6. Expected fractional damage when MAE_{bldg} is 1000 m^2.

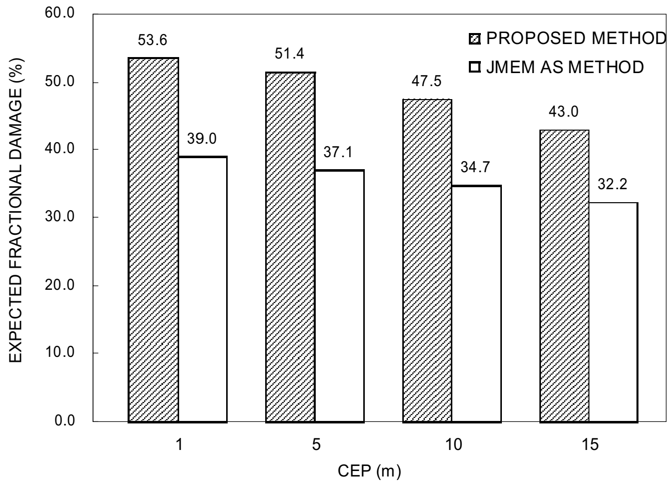
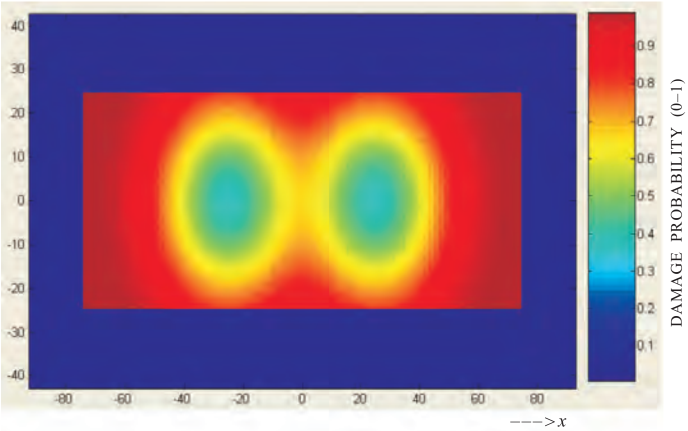
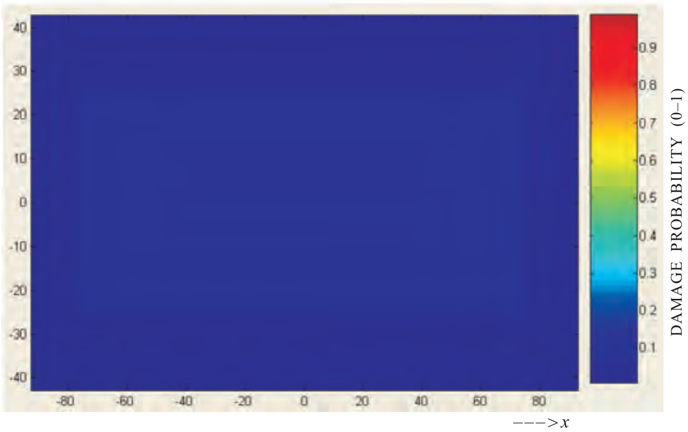


Figure 7. Expected fractional damage when MAE_{bldg} is 2000 m^2.



(a)



(b)

Figure 8. Comparison of expected fractional damages from: (a) the proposed method (23.7 per cent), and (b) JMEM/AS methods (16.9 per cent).

5. CONCLUSIONS

A model to calculate expected fractional damage for building targets was developed based on the indirect fire concept. It has been shown that the conventional JMEM/AS method could not be an appropriate tool for the damage calculation of building targets in both single and multiple aiming point cases. Since recently developed weapon systems have smaller warheads and have more accuracy compared to past weapons, the main purpose could be a precise destruction of a certain part of building rather than the demolition of the whole building. In that case, the proposed model could be a good approach.

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