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APPLICATION OF MILITARY BLAST EFFECTS EXPERT SYSTEM TO MODERN FORCE PROTECTION STRUCTURES

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ABSTRACT

Defence R&D Canada has developed and evaluated military structures for field fortification and camps. Typical structures include: trenches, personnel collective protection, observation posts, tents and storage facilities for water, fuel and ammunition. In support of this work, a Military Blast Effects Expert System (MBEES) has been developed to facilitate the design and deployment of these structures, and to assess their vulnerability to conventional and enhanced blast weapons. MBEES consists of four modules:

1. Explosives and Weapons Module: calculates blast properties for a variety of HE, FAE, thermobaric weapons and terrorist improvised explosives.
2. Structures and Scenes Module: provides easy visual set-up of structures and camp layouts, and graphical presentation of the blast loading and structural response.
3. Loading, Response, Design and Vulnerability Module: calculates the blast loading and structural/human response, and evaluates the overall damage to the structure. Blast loading is based on a collection of sub-models for external loading and ingress. These models combine semi-empirical models with an extensive library of computational fluid dynamics results. The structural response algorithms assess blast-induced deformations, including bending, shear and torque deformations. This response is computed using a semi-empirical three-degree-of-freedom model and a structural mechanics based continuous system model. Blast and response models are combined for an overall vulnerability assessment of structures and their occupants.
4. Field Advisor Module: guides the user in the construction and deployment of the structures.

The modules, including blast and structural response models, are reviewed. Applications to typical force protection structures are presented. Due to construction methods and locations, requirements for military structures can be quite different from urban structures. Some important factors for military structures include: the possibility of attack from a wide variety of threats, the highly ductile materials used in the construction of gabion-based structures, and the blast protection measures used in the overall structural design.

INTRODUCTION

Defence R&D Canada – Suffield (DRDC Suffield) is in the final year of a four year technology demonstration program on Force Protection Against Enhanced Blast (FPAEB). The overall goal of the program is to improve personnel safety in deployed structures. The project objectives include: determining the limits of enhanced blast weapons; assessing currently deployed structures; designing and testing new deployable structures; developing a rapid rating scheme to rate the blast vulnerability of urban buildings; and create a tool to design deployed camps and quickly assess the vulnerability of these camps. The Military Blast Effects Expert System (MBEES) has been developed in response to the last objective. Additionally, MBEES is used to determine blast properties of traditional and novel explosives (e.g., TNT, fuel air, thermobaric), and provide instructions/advice on basic camp construction. As an expert system, MBEES was designed to quickly provide answers to vulnerability questions. Whereas previous expert systems and simulation software packages have mainly been designed for urban structures and city environments [1-10], MBEES focuses on military structures and camps.

MBEES consists of four modules: the Explosives and Weapons Module (EWM), the Structures and Scenes Module (SSM), the Loading, Response, and Vulnerability Module (LRVM), and the Field Advisor Module (FAM). The SSM and LRVM are based on AutoCAD, whereas the EWM and FAM are web-based programs that can be used independently from the AutoCAD platform. As shown in Figure 1, the four modules have been developed to address the needs of a wide variety of users involved in threat/vulnerability assessment, protective structure design and deployment. MBEES is designed such that data and output from each module is used by subsequent modules.

MBEES users must address a large number of threat-target combinations and complex camps that can involve hundreds of structures. For this reason, the blast, structural response and human vulnerability calculations must be performed quickly while remaining sufficiently realistic and accurate. This fact, combined with the novel structures used in modern camps, has necessitated the development of new blast models using CFD-constructed look-up tables and fast-running multi-degree-of-freedom structural response models.

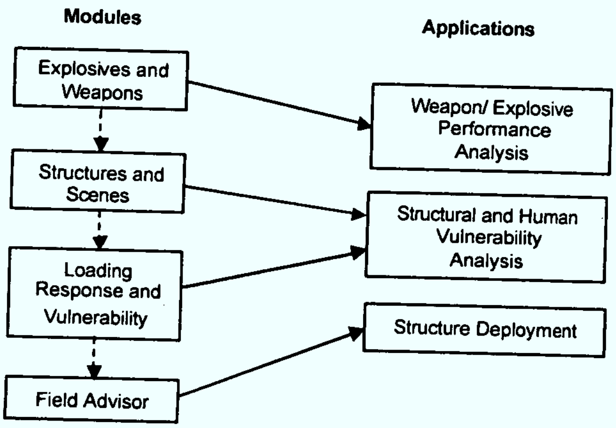


Figure 1. MBEES Modules and Applications

THE MODULES

Explosive and Weapons Module

The Explosives and Weapons Module (EWM) calculates blast properties for a variety of military weapons and improvised explosives. These include common military HE threats, such as those found in the Conwep [11] software, and other munitions based on FAE, thermobaric, and improvised explosives used by terrorists. Explosive mixtures can also be defined based on component compositions.

The EWM is an Internet Explorer^{TM} web-based application that uses an open XML database to store explosive/weapon data, models, references and units. This database also contains the relevant information to allow automatic menu generation and plotting when new threats and property types are added. This approach facilitates the addition of new threats and performance data. The EWM database currently includes:

1. General properties (eg. density and composition)
2. Detonation properties for explosives
3. Quasi-Static-Pressure (QSP) properties
4. Blast properties (spherical, hemi-spherical; incident and reflected)

EWM provides both text and graphical output and, as shown in Figure 2, displays nominal and lower- and/or upper-bound data when available. The software also provides comments on the data source and estimated quality. Bound and quality assessments are particularly important for non-ideal thermobaric and improvised explosives which are susceptible to scaling effects. Finally, the EWM provides a searchable database of references with links to available documents.

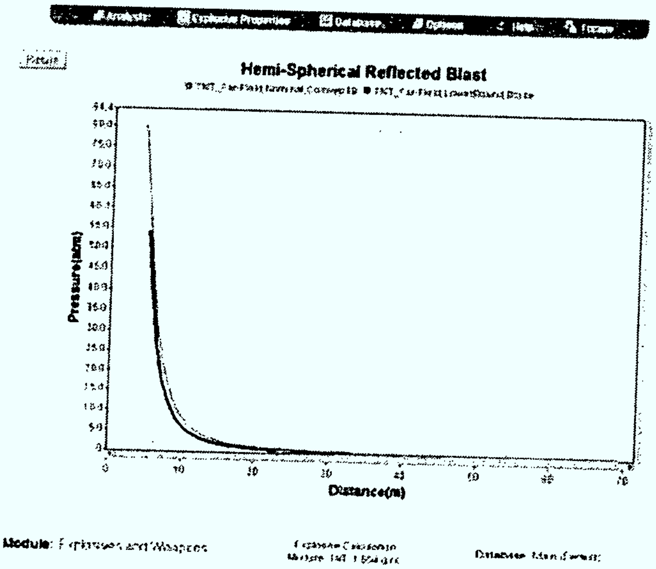


Figure 2. Sample Output from Explosives and Weapons Module

Structures and Scenes Module

The Structures and Scenes Module (SSM) provides easy visual set-up of structures and camp layouts, and graphical presentation of the blast loading and structural response. Since this module is developed as an AutoCAD-based module, it provides the full graphical capabilities of AutoCAD, while providing a customized user interface for MBEES users. The user can select any threat from the Explosives and Weapons Module database and construct a structure based on one of the structure types shown in Figure 3. As shown in Figure 4, specific structures can be defined by assigning values to the various structure parameters. The structures and threats are contained in an overall scene, which in the case of a camp, can contain a large number of structures (Fig. 5).

The Structures and Scenes module provides a user shell for access to the other MBEES modules or any third-party software on the user's computer. It also provides detailed reports of calculations by generating PowerPoint files based on user-defined scripts.

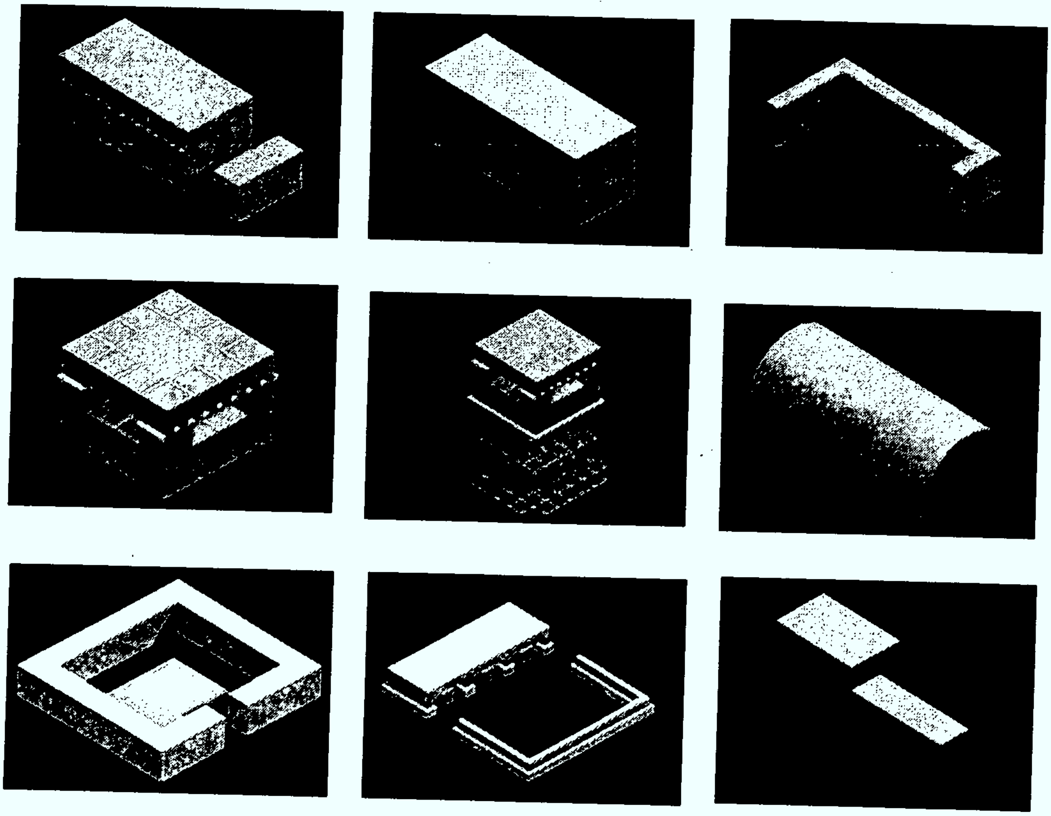
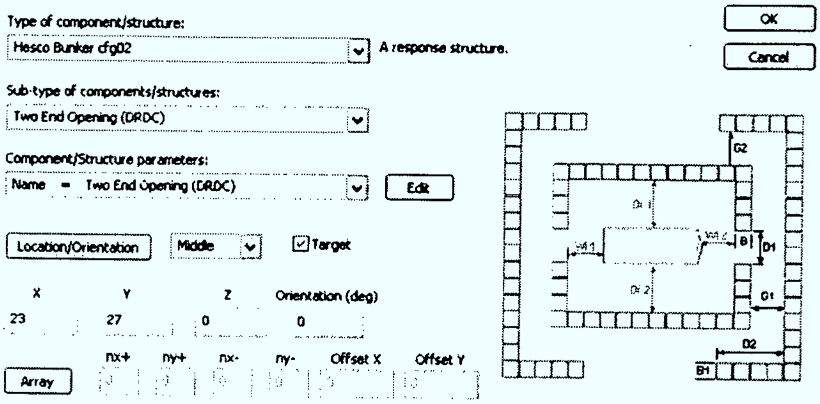


Figure 3. Some structure types included in the Structures and Scenes Module

From left to right and top to bottom: bunker, ISO container, protective wall, ground observation post, elevated observation post, tent, fuel/water bladder with protective wall, ammunition storage facility with protective wall, and combat trench.



Type of component/structure: Hesco Bunker cfg02

A response structure.

Sub-type of components/structures: Two End Opening (DRDC)

Component/Structure parameters: Name = Two End Opening (DRDC)

Middle

☑ Target

X	Y	Z	Orientation (deg)
23	27	0	0

nx+ ny+ nx- ny- Offset X Offset Y

Figure 4. Typical parametric input for bunker type structure

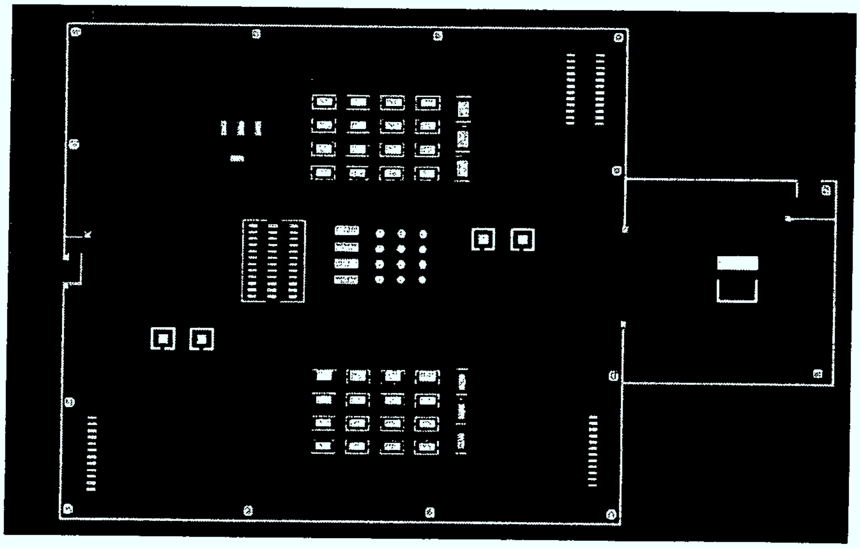


Figure 5. Generic camp structure

Loading, Response and Vulnerability Module

The Loading, Response, and Vulnerability Module (LRVM) is included in the Structures and Scenes graphical interface and allows users to perform blast, structural response and human vulnerability calculations. Calculations may be performed for a specified target position or for a grid of possible charge locations. In the former case, the software provides colour contours for blast loading pressures and impulses, and deformation plots for gabion walls used in modern protective structures (Fig.6). Human vulnerability data is presented in the form of a spreadsheet for different occupant positions and orientations in the structure (Fig. 7). Structures that have exceeded specified thresholds for structural damage or human vulnerability blink in the scene to alert the user of their vulnerability. If a grid of possible charge locations is provided, the software provides iso-vulnerability contour plots for structural and human response. As shown in Figure 8, these can be two-dimensional colour plots when the charge is located on the ground, or three-dimension iso-vulnerability surface plots when the charge height is allowed to vary in the analysis.

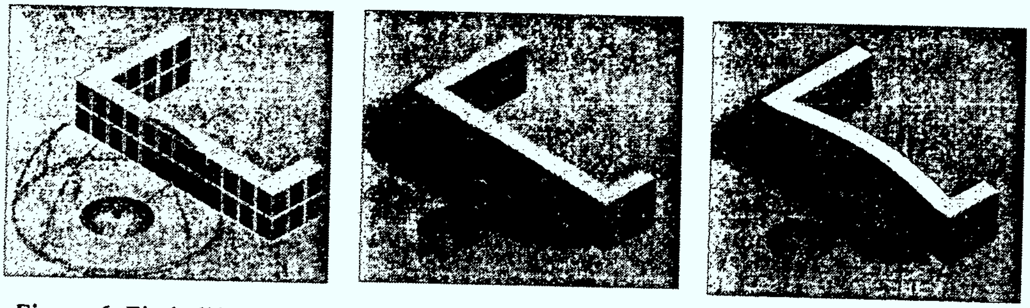


Figure 6. Fireball/Blast loading, crater and wall deformation plots for a protective wall

	Best Location (1)	Mean (2)	Worst Location(3)
Best Body Orientation	31.39	24.78	100.00
Worst Body Orientation	99.59	99.23	100.00
Average Orientation	65.49	62.01	100.00

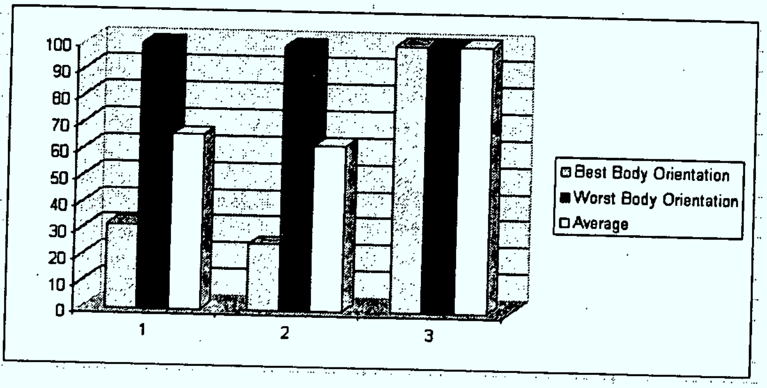


Figure 7. Human vulnerability data display

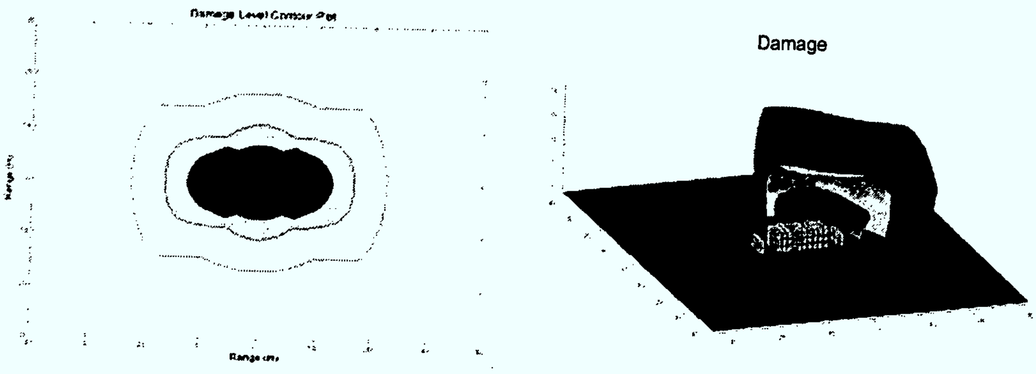
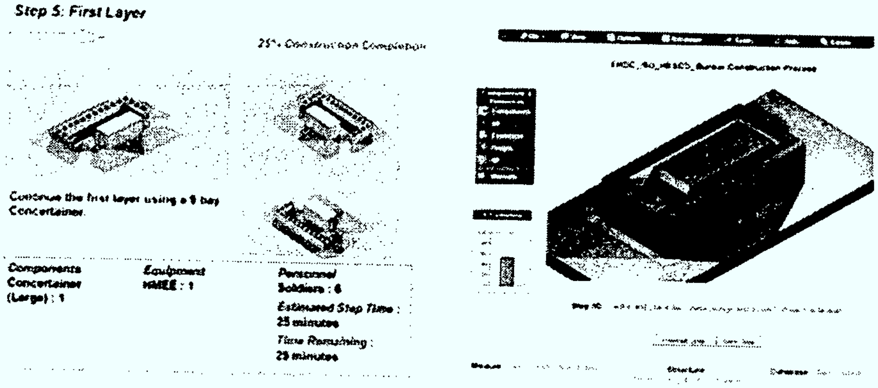


Figure 8. Sample 2-D colour contour plot and 3-D iso-vulnerability surface plot.

Field Advisor Module

The Field Advisor Module (FAM) guides the user in the construction and deployment of the structures. This module provides data concerning the structure's components and the labour and heavy equipment required for its construction. It also includes vulnerability contours for different threats. The FAM is available either as a PowerPoint presentation, which can be readily displayed on a small PDA (Fig. 9b), or as a web application that can run on a laptop computer (Fig. 9a).



Step 5: First Layer

25% Construction Completion

Continue the first layer using a 9 bay Concertainer.

Components
Concertainer (Large) : 1

Equipment
HMEE : 1

Personnel
Soldiers : 6

Estimated Step Time : 25 minutes

Time Remaining : 25 minutes

Figure 9. Sample display from the Field Advisor Module. Left: PDA PowerPoint for HESCO-ISO Bunker, Right: Web application displaying, as an example, an ERDC HESCO-ISO structure with construction procedures [12].

Overall Development Approach

MBEES was developed using an incremental approach. The original development plan for MBEES included only one structure: a bunker constructed of an ISO container surrounded by sand-filled gabion baskets. The modules were developed and tested with this bunker. Thus, the concepts and all four modules were proven viable, and design improvements were addressed early in the development. Once all the modules were working, MBEES development proceeded (and continues to proceed) laterally, that is, more structures are continually being added. In addition to the original bunker, tents, trenches, observation posts (OPs), munitions storage facilities, walls, fuel/water bladders and another type of bunker have been added.

MODELS FOR BLAST LOADING, STRUCTURAL RESPONSE AND HUMAN VULNERABILITY

MBEES users must address a wide variety of threat/target combinations and analyze camps that can contain hundreds of structures. Furthermore, vulnerability contour assessments for a particular threat-target combination may involve 100 – 5,000 separate calculations depending on the contour resolution and dimensionality (2-D or 3-D). For these reasons, MBEES can only be successfully used if individual calculations can be run quickly with realistic and sufficiently accurate models. For a blast loading calculation, this is achieved by combining semi-empirical models with multi-dimensional look-up tables based on many thousands of

CFD calculations. Structural response models in MBEES vary from simple damage threshold models to more detailed fast-running, multiple-degree-of-freedom models.

Blast, Fireball and Crater Models

Blast loading of protective structures involves a wide variety of external and internal blast phenomena. The blast analysis is further complicated by the slow response of commonly-used gabion structures that deform over a time scale as long as one second. For most anticipated threats, this time scale is much longer than the duration of the positive phase of the blast profile. Consequently, additional models must be included to address the negative phase which can have a significant effect on the total impulse.

MBEES currently has sub-models for the following phenomena:

- Normal and oblique blast reflection,
- Impulse reduction due to "clearing" effects on front face ,
- Mach stem for elevated charges,
- Blast focusing,
- Blast diffraction around corners (including vortex effect on total impulse),
- Blast loading on rear face,
- Ingress into structures,
- Egress out of structures,
- Blast shielding from neighbouring structures,
- Positive and full-impulse loading

In addition to the above phenomena, MBEES computes hemi-spherical and elliptical fireballs for HE and FAE explosives, respectively, and crater dimensions for HE explosives as a function of the soil type. Although a comprehensive description of the above sub-models is beyond the scope of this paper, the following general observations are presented on the overall model development.

Scaling Parameters:

Blast models can be developed using geometric and explosive mass scaling laws. Geometric scaling variables include, for example, the aspect ratio of a structure or the ratio of a protective wall height to its distance from the structure that it is shielding. Hopkinson-Cranz [13, 14] mass scaling is commonly used to present free-field blast results as a function of the scaled variable, $X/M^{1/3}$, where X is the charge standoff distance and M is the charge mass. For blast clearing calculations, Rose and Smith [15] introduced an additional parameter $H/M^{1/3}$, where H is the height of the structure. Through detailed 3-D CFD calculations, these authors developed a useful look-up table that allow the calculation of the average impulse reduction on a front face due to clearing as a function of these two mass-scaled variables. Their work emphasizes the need to develop models that are valid for the range of $X/M^{1/3}$ and $H/M^{1/3}$ expected in the application of the model. MBEES uses the Rose and Smith look-up table to calculate the average impulse reduction due to clearing and adds an additional wave clearing model to determine how the impulse reduction is distributed over the front face. This model is based on a characteristic time for an expansion wave to propagate from the edge of a structure to the target position. The model uses an additional parameter which is calculated, using CFD calculations, and expressed as a function of the two mass-scaled variables. Many of the blast models used in MBEES are based on mass-scaled variables and a series of additional geometric scaling parameters. Supporting 3-D and 2-D CFD calculations for the multi-dimensional look-up table development have been performed for the range of parameters expected in MBEES applications.

Full impulse calculations:

As previously mentioned, the long response time of gabion structures implies a need to account for the negative phase contribution to the total impulse. For incident blast waves, the ratio of the negative-to-positive impulse is approximately 0.85 over a wide range of scaled distances [16]. For reflected impulses, the ratio of the two impulses varies approximately between 0.6 and 0.8 for scaled distances between 3 and 10 $ft/lb^{1/3}$ [17]. MBEES addresses this issue by adding a CFD-constructed look-up table for the impulse reduction due to the negative phase. Total impulse calculations using CFD can be considerably longer than for the positive phase since the negative phase is usually much longer than the positive phase. A much larger computational grid is also required to prevent inaccuracies from propagating from the edges of the computational domain to the target position. For this reason, the correction factors are estimated based on 2-D axi-symmetric calculations for end-on blast propagation over a hemi-cylinder.

Blast ingress:

Blast ingress into a structure results in a complex shock reflection pattern inside the structure. For internal explosions, this pattern can be calculated using CFD methods or by applying ray tracing techniques with non-linear addition rules. The application of the latter approach to blast ingress is more difficult due to the shock diffraction that occurs at the entrance. The ingress process is further complicated by protective walls that are usually in close proximity to the entrance. For MBEES applications, the main purpose of the blast ingress calculation is to assess the human vulnerability which is sensitive to the pressure peaks. Since the magnitudes of these peaks are very sensitive to the precise location of an occupant inside the structure, detailed blast calculations for a small number of monitoring positions do not necessarily provide meaningful results for the overall vulnerability. Due to these difficulties, MBEES uses a look-up table that contains means and standard deviations of peak pressures and characteristic durations for different regions inside a structure. This multi-dimensional table is expressed in terms of the volume of the structure, the characteristic structure aspect ratio, the scaled ingress and egress areas and the characteristic pressure and impulse at the entrance of the structure. The table is constructed through thousands of CFD calculations, each with hundreds of monitoring points. These calculations are once again 2-D axi-symmetric to reduce the computational effort.

Structural Response Models

The structural response models vary in complexity from a simple damage threshold to multi-degree-of-freedom models. The latter are used for gabion walls that respond relatively slowly to the total impulse. These walls are also highly ductile and can deform significantly before total collapse. MBEES uses two optional approaches to model this deformation. Both methods are based on governing equations for the displacement, u_y, in the direction of the blast, y, and rotations, θ_x and θ_z, about the x and z axes respectively.

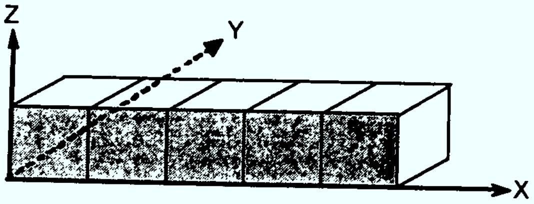


Figure 10. Coordinate system or structural response models

The three-degree-of-freedom model uses a virtual work method and polynomial shape functions to derive a set of three ordinary differential equations. Coefficients for the shape functions are derived for different boundary conditions corresponding to straight, L-shaped and U-shaped walls. No-slip conditions are assumed at the ground and bading from the roof is modeled as a motion damping force. For straight walls, the shape function is amended to take into account the position of the charge which affects the location of maximum displacement.

The second 'continuous' model approach solves the first order terms of the governing equations using analytical methods. The model can accommodate fixed and/or free boundary conditions at the ends, no-slip conditions or a friction force on the ground, and a moment boundary condition at the roof. A higher-order, large-deformation model that includes a non-linear strain-displacement relationship was also developed and found to give similar results as the simpler lower-order solution.

Both models include material properties for the fill material and a model for the ground response. A sensitivity study performed for the seven constants in the models indicates that the results are most sensitive to the material density, the shear and Young's modulus, the shear strength and a fill compression coefficient. The sensitivity to the shear parameters is more pronounced for U-shaped and L-shaped walls than for a straight, free-standing wall. The results are also sensitive to the ground response parameter for straight, free-standing walls due to the large rotations. The value for this parameter was calibrated based on experimental trials.

MBEES offers options to use either the 3-DOF or continuous model, or a hybrid approach where the free-standing wall response is calculated using the 3-DOF model, while the response of the remaining walls is calculated using the continuous model. Figure 11 displays a comparison of computed and experimental damage for a bunker structure.

An overall damage assessment of a structure is performed based on the damages to the individual cells and walls. As shown in Figure 12, cell damage results in loss of fill, which reduces the height of the wall and the roof stability. The wall deformation and shortened height is then taken into account in the overall structural damage assessment.

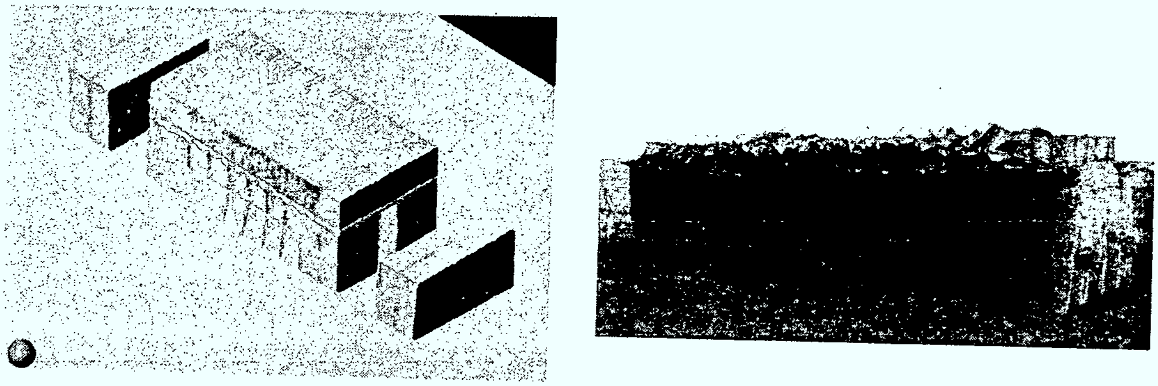


Figure 11. Computed and experimental damages for bunker structure

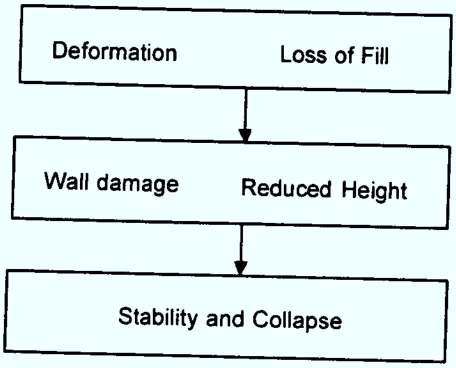


Figure 12. Calculation sequence for structural damage assessment

Human Vulnerability Model

MBEES calculates the human vulnerability caused by blast-induced lung damage. Such a calculation remains difficult for blast ingress problems due to the complex shock pattern inside the structure. The most accurate approach to this problem is to compute the detailed flow field in the structure including the occupant(s). The blast loading history on each occupant can then be used in a cylinder lung response model such as that developed by Axelsson and Yelverton [18] to determine human injury. Unfortunately, due to the high resolution required to resolve the flow field around the cylinder, this approach does not lend itself easily to the development of a fast-assessment model that requires a large number of CFD calculations to construct a database. Efforts are currently under way at DRDC to produce a correlation that would only require time-history properties at the location of the occupant, without the latter being in the flow field. As an interim approach, MBEES currently estimates the human vulnerability based on a revised form of the free-field vulnerability data of Bowen [19].

CONCLUSIONS

This paper has reviewed the main features of the Military Blast Effects Expert System (MBEES) that has been developed in support of the DRDC Force Protection Against Enhanced Blast (FPAEB) technology demonstration program. MBEES provides fast-running computational tools for threat assessment, vulnerability analysis and structural design. A specialized module is also included to guide the deployment of military protective structures. The blast, structural response and human vulnerability models address specific requirements associated with military structures deployed in camps that can include a large number of structures. MBEES calculations for blast, structural response and personnel vulnerability can be performed in under a minute for one gabion structure, while results for a generic camp are computed in approximately 15-30 minutes.

The development of suitable computational tools must address construction features that are specific to modern military protective structures. Due to construction methods and locations, requirements for military structures can be quite different from urban structures. Some important factors for military structures include: the possibility of attack from a wide variety of threats, the highly ductile materials used in the construction of gabion-based structures, the long response time of these structures and the blast protection measures used in the overall structural design. Finally, since modern military structures are much more blast resistant than their urban counterparts, the human vulnerability can become dominated by blast ingress which involves complex shock reflections. Improved fast-running human vulnerability models are currently needed to address such complex blast environments.

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