Transactions, **SMiRT-22**
San Francisco, California, USA - August 18-23, 2013
Division IX

USE OF HIGH-FIDELITY PHYSICS-BASED ANALYSES IN THE QUALIFICATION OF BLAST/BALLISTIC CERTIFIED BUILDINGS FOR INFRASTRUCTURE SECURITY

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ABSTRACT

Access control is a critical component of infrastructure security. Large explosive detonation has been used as an initiating event for attacks on restricted spaces, with the goal of gaining access. Protection of security personnel during a blast event is of upmost importance for denying access to attackers. Protection can include the use of blast/ballistic certified building (BBCB) structures at site access points. The structural design must be comprehensive to not only insure stability of the structure but also insure survivability and continued performance of the resident security personnel. At the same time, the structure must be economical in design and construction. Design support with high-fidelity physics-based computer codes can greatly help BBCB structures meet these criteria and provide response validation for site specific criteria without the time and expense of explosive testing. Computational fluid dynamics calculations provide more accurate characterizations of blast pressures on BBCB structures for defined threats compared to simplified design tools, particularly for structures with complex geometries. Nonlinear explicit finite element analyses accurately predict structural responses to not only evaluate stability of the structure during a blast event but also the responses of structural components and connections. The resolution of the analysis results is much higher than results produced with simplified methods such as single-degree-of-freedom calculations, and such detailed information can be used to optimize the design of the structure for economy. Finally, these detailed calculations provide insight into the pressures inside the BBCB enclosure to help determine a level of protection afforded to the resident personnel.

INTRODUCTION

Blast/Ballistic certified buildings (BBCB), placed at perimeters of restricted spaces, protect security personnel from external threats vying to gain site access. Such threats may include large explosive detonations, such as from a vehicle-borne improvised explosive device (VBIED). The BBCB, whether ground-based or elevated by a support tower, must be robust enough to withstand the blast effects and provide protection to its inhabitants so that they can continue to provide site protection post-event. Given today's economic climate, the structure must also be efficient in design and construction.

This paper presents computational work performed by Weidlinger Associates, Inc. (WAI) to assess and validate the responses of BBCB structures to large explosive detonations. The BBCB structures are designed and constructed by Kontek Industries, Inc. While the high-fidelity physics-based computer codes used are more computationally intensive than simplified methods, it will be shown that the high level of detail provides benefits not attainable by simplified methods, and the effort spent during modeling and analysis can lead to economies in design, while also providing validation of the structure's performance and robustness. The paper begins with a description of the BBCB structure. This is followed by a discussion of the analysis methods used to calculate airblast pressures and structural responses and their benefits over simplified methods. These calculations also provide data that can be used to assess the environment inside the BBCB during a blast event, critical to assessing the level of protection afforded to the inhabitants by the BBCB. Finally, a summary of the findings and conclusions are offered.

BLAST/BALLISTIC CERTIFIED BUILDING (BBCB)

The BBCB structures discussed in this paper are designed and constructed by Kontek Industries, Inc. Examples of constructed BBCBs are shown in Figure 1. These structures are composed of multiple steel panels through the floor, ceiling, and wall thicknesses. The windows and weapon firing access ports are blast/ballistic certified. The structures may be insulated and may be outfitted with HVAC systems. The structures may be located on grade or may be mounted on steel towers.

Figure 1. Examples of blast/ballistic certified buildings (Kontek, 2013).

AIRBLAST CALCULATIONS

The task of computing the response of a structure to an open-air detonation begins with determining the airblast pressures on the surfaces of the structure. There are two widely used methods for quantifying these transient pressure histories: using simplified tools or performing numerical analyses based upon computational fluid dynamics (CFD). One commonly used simplified tool is CONWEP (Hyde, 2007). CONWEP uses equations based upon curve-fitted data from open-air detonations of TNT to determine reflected pressure time histories on surfaces. CFD codes use numerical methods to solve the partial differential equations governing explosive detonation and wave propagation through a fluid (such as air), returning among their output incident and reflected pressure time histories on surfaces.

WAI uses the CFD code MAZ (Schlamp, et al., 1995) to determine the blast pressure time histories for BBCB response calculations. Using CFD codes requires an experienced analyst and time to discretize the geometries of the target structure and surrounding region and perform the analysis, and so requires more time and effort than using simplified tools. But the benefits to the CFD effort compared to simplified tools are many. Some of these benefits are discussed next.

Scaled standoff is defined as $Z = R/W^{1/3}$, where R is the range [ft] and W the charge weight [lb]. WAI's experience has shown, through modeling and field validation, that simplified tools such as CONWEP lose accuracy for Z values less than one. Simplified tools also adopt either a spherical or hemispherical shaped charge. For close-in threats with Z values less than one, charge shape is a dominant factor, and assuming a spherical or hemispherical charge shape can drastically underestimate the airblast pressures (Hassig, McArthur, Tennant, & Lawver, 2007). CFD codes can model detonations of more complex and realistic charge shapes such as cylindrical and rectangular charges, and in doing so provide more accurate pressure calculations. For example, Hassig's study shows that for values of Z less than one, a rectangular shaped explosive charge delivers a load to a planar target that can be four times larger than a spherically-shaped charge of the same weight. This difference has a dramatic effect on the structural response. Conversely, for large standoffs simplified tools can be overly conservative, because simplified tools do not take into account the effects of a structure's geometry on blast pressure (Hassig, Tennant, Weeks, & Levine, 2009). Specifically, CFD calculations can capture the fluid flow around the corners of the actual geometry of a structure, while simplified calculations are independent of the target's actual geometry. Calculating the fluid flow around the structure captures what are called "clearing effects", where the blast load is shed around corners, resulting in a reduction of the total loads applied to those faces of the structure normal to the blast.

An example is now provided comparing CFD calculation results using MAZ to CONWEP for an elevated BBCB at a large scaled standoff of Z > 5. The CONWEP calculation uses a hemispherical charge shape, while the MAZ calculation uses a more realistic cylindrical shape. Figure 2 compares the contour plots of peak pressure, normalized to the CONWEP peak. The more accurate representation of the structure's geometry and its effects on the blast pressures in the CFD analysis is clearly shown, particularly at the edges of the structure where the fluid flows around the corners, decreasing the peak pressures. The lower pressures calculated by the CFD analysis translate to lower impulses as well, as shown in Figure 3, where impulse is the integral of the pressure time history, or the total energy delivered by the airblast. On the global level, the total lateral force delivered to the BBCB by the airblast can be calculated by both methods, and this is cross-plotted in Figure 4. As shown, the CONWEP calculation applies almost twice the total lateral force to the BBCB as the CFD calculation.

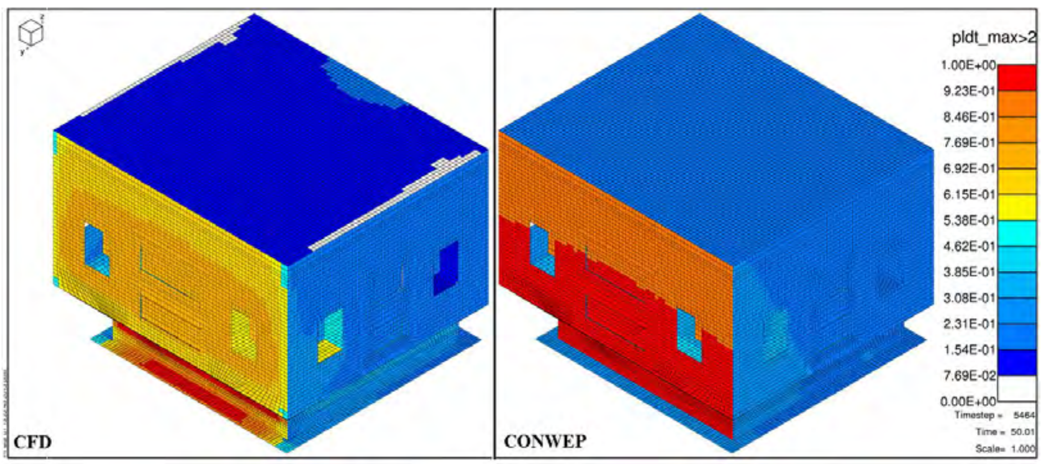

Figure 2. Comparison of normalized peak pressure by (left) CFD and (right) CONWEP.

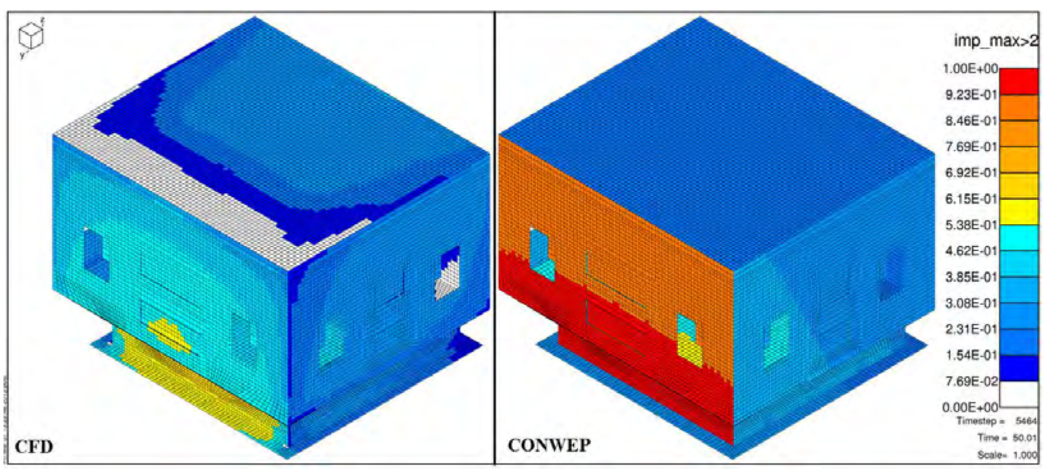

Figure 3. Comparison of normalized peak impulse by (left) CFD and (right) CONWEP.

Calculating the most accurate airblast pressures is critically important for the design of a BBCB that both exceeds performance requirements and is economical. Underestimating the airblast pressures is obviously detrimental to achieving a design that exceeds performance requirements in terms of structural response and personnel protection. Overestimating the airblast pressures can lead to a more costly design. Accurate airblast calculations help achieve both goals.

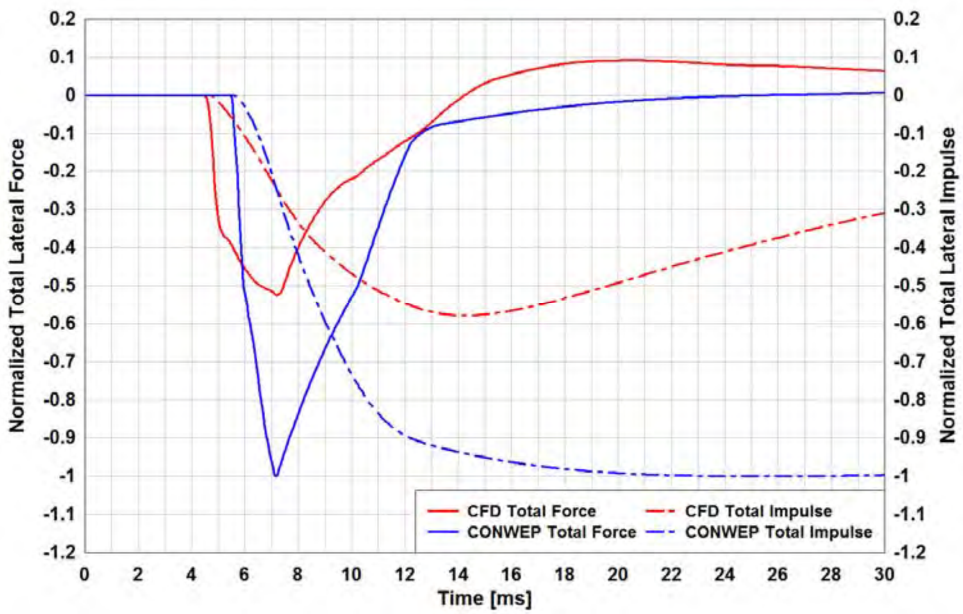

Figure 4. Comparison of normalized total lateral force applied to a BBCB by CFD and CONWEP.

STRUCTURAL RESPONSE CALCULATIONS

The structural response calculations presented here are performed with WAI's proprietary code NLFLEX (Vaughan, 1983 plus updates through 2013), a commercial grade nonlinear, transient analysis finite element code. NLFLEX has been validated through pretest predictions and post-test correlation with small-scale and large-scale tests for a large number of airblast, impact, ground shock and thermal loading situations. Above-ground, surface-flush, shallow-buried and deeply-buried structural responses have been simulated for both civilian and military construction. NLFLEX is listed as an acceptable code for blast analysis in UFC 3-340-01.

The finite element analyses investigate two response regimes, in order of importance:

1. Global response: The analyses investigate the response of the BBCB, and the BBCB with support tower if it is elevated, to determine if the structure fails on a global level. Global failure is defined by failure of the structure to serve its function of providing blast and ballistic protection to the occupants. Global failure may manifest by complete or partial collapse of the BBCB, breach of one or more of the BBCB surfaces, or separation of the BBCB from its foundation. If the BBCB is elevated by a tower, global failure may manifest by overturning of the structure.
2. Local response: The analyses investigate local responses of the BBCB on a component level. This includes component (doors, window frames, gun ports, etc.) yielding or failure, connection yielding or failure, displacements of the floor, ceiling, and wall panels, and interactions between the sandwich panels composing the floor, ceiling, and walls of the BBCB. If the BBCB is elevated by a tower, the tower framing components and connections are investigated for localized failures.

Global failure must obviously be avoided. Localized inelasticity and even localized failure may be tolerable if it does not reduce the function of the BBCB during the event and is repairable post-event.

The level of detail in the finite element models and analyses must be high in order to capture the global and local responses of the BBCB and support system. Blast is an inherently dynamic event, with the event occurring in a time frame measured in milliseconds, and the structural response occurring over hundreds of milliseconds, or up to a few seconds in extreme cases of collapse. To accurately capture responses in this time frame, the preferred analysis method uses explicit time integration. Explicit time integration also avoids numerical issues that can arise when modeling events that induce structural failures. Algorithms that properly account for geometric and material nonlinearities are also required. The NLFLEX code meets all of these requirements.

Consider the example finite element models shown in Figure 5. The BBCB structures are supported by steel towers sitting on concrete foundations resting on in-situ soil. Steel components, such as the plates in the BBCB walls, floor, and ceiling, or the tower columns and framing, are modeled using four-noded shell elements. The foundations and soil are modeled using hexahedral continuum elements. The following paragraphs describe the analysis and modeling details applied to these models to accurately capture the global and local responses of the designs to an explosive event.

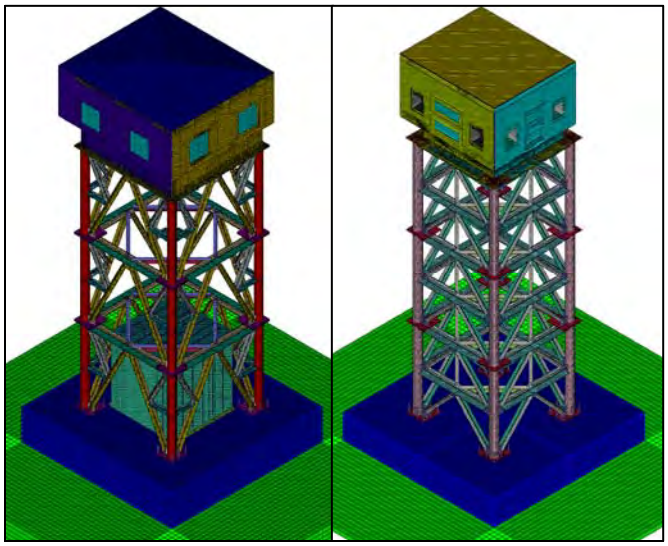

Figure 5. Example finite element models of BBCB structures atop steel towers.

Global collapse of the BBCB and/or the entire structure, and local failures of individual components, will involve large displacements and cause large strains in the materials. The geometries of the structure and its components will significantly change in a nonlinear manner. To capture these effects, the analyses adopt a large strain and displacement formulation.

Large strains push material strengths past their elastic limits. Plasticity and damage-based material models are used to capture the nonlinear material responses. Metals, such as the A36 steel used to form the BBCB wall panels, are modeled with a von-Mises plasticity-based piecewise linear hardening constitutive model with softening and rate effects. The uniaxial tension responses for these metal models are fit to ASTM data when available. Concrete and soil are modeled with WAI's three invariant plasticity-based constitutive model with isotropic damage-based softening (Mould & Levine, 1993). The concrete model is fit to all available test data, or in the absence of test data the model is fit to the specified unconfined compressive strength of the design concrete. The soil model is fit to properties of the site-specific in-situ soil properties when available.

Modeling details are very important in order to capture the correct responses of the structures under blast loading. Often, trying to simplify the modeling of a complex structure will result in missing critical response modes. Two important issues are construction and connections. The BBCB structures are modeled as close to the actual designs as possible. The BBCB walls, for example, are composed of multiple plate layers, connected with perimeter angled that leave air gaps between the plates away from these connectors. These plate layers can and will interact with each other as they deform under blast loading. It would be difficult to capture such interactions with a simplified, single layer representation.

So the finite element analyses model these built-up walls as they are constructed. Figure 6 shows two examples of model details for a BBCB wall and floor. The left image shows the butt joint where two walls meet. The two inner plates in one wall panel stop short of the inner plates in the adjoining panel, while the exterior plates in both panels intersect for welding. A similar condition is modeled where the wall panel meets the floor, with the inner wall plates stopping short of the floor and the exterior plate meeting the floor plate for welding. Slideline interaction logic is applied to the adjoining surfaces that are not mechanically connected, such as where the inner wall plates and connection angles butt against the adjacent inner wall plate in the left image of Figure 6. Under large deformations, these adjacent components could collide, and the slidelines captures the interactions. The wall panels themselves could impact each other during blast loading, so steps are taken to model these possible interactions as well. The wall panels are separated by air gaps whose thicknesses are known. A difficulty is introduced due to the fact that while the actual metal wall plates have finite thicknesses, the shell elements used to model the plates have zero thicknesses. The shells are located spatially at the centers of gravity of the wall plates. Due to the zero thickness shells, the "air gaps" between the shell layers are greater than the actual air gaps in the design. Applying slidelines to model the interactions between the shell layers would therefore allow larger deformations before contact (½ of plate 1 thickness + design air gap + ½ of plate 2 thickness, verses just the design air gap), and larger deformations lead to larger strains in the shells. So instead of using slidelines, nonlinear springs are defined between the nodes of the adjacent shells representing the wall plates. These springs are tuned to allow for free expansion (plates may move away from each other) and to compress freely down to the design air gap width before locking up, thus capturing the interaction between the adjacent wall panels. The spring provides zero force while elongating, representing the adjacent wall panels' freedom to move away from each other with no restraint. Under compression, the spring provides zero force while the air gap closes between the adjacent plates. Once the air gap is closed, the spring force is based upon the bulk moduli of the plates, representing contact. Accurate modeling of connections is equally important, and spring elements are used for this as well. Bolted connections are modeled as accurately as possible within the resolution of the finite element grid. Gusset plates, connection angles, and other related steel sections are modeled with shells. Individual bolts are modeled with groups of three springs to capture both axial and shear responses. The spring stiffness is based upon piecewise linear fits to the axial response of the actual bolt type, taken from ASTM standards. Separate cross-sectional areas can be specified for axial and shear resistances to account for bolt threads being included or excluded from the shear plane. Welded connections are also modeled, and can be modeled two ways. For continuous welds, the "weld" is simulated through translational and rotational compatibility between the connected members. Element

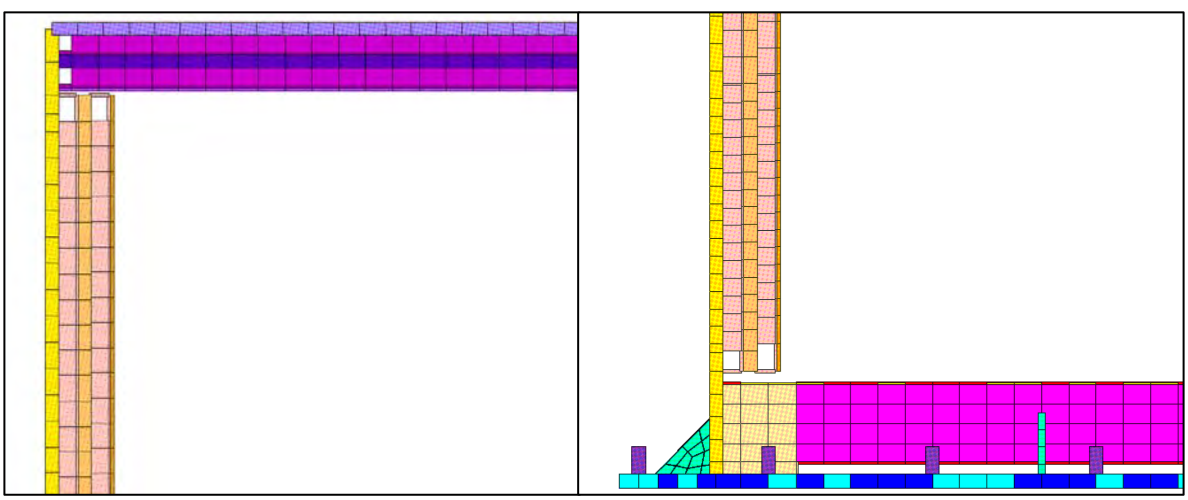

Figure 6. (left) Horizontal section through BBCB modeled wall joint, (right). Vertical section through BBCB wall and floor joint.

failure on either side of the connection then indicates possible connection failure. For shorter weld lengths, or welds considered to be weaker than the connected members, springs are fit to the weld force-displacement responses in the three orthogonal axes.

The structural response analyses are performed in three phases. The first phase applies gravity and allows the structure to settle to its stable, pre-blast condition. The second phase applies the blast pressures previously calculated by the CFD analyses and runs the analyses through the blast duration. The CFD and structural response analyses are uncoupled (structural response does not affect airblast pressure). The third phase continues following the structural response until failure or stability is apparent. Figure 7 shows an example of a system response to blast loading. The left figure shows peak lateral displacement contours of the model in response to the blast pressures, moving in the direction of the blast waves. The right figure shows displacement time histories along the structure height through the initial blast response and first rebound. This example shows the system responding very much like a cantilever, with the highest responses seen at roof level. The oscillating nature of the lateral displacement time histories is an indication of structural stability. Validation of stability can also be attained through time histories of total momentums of the structure.

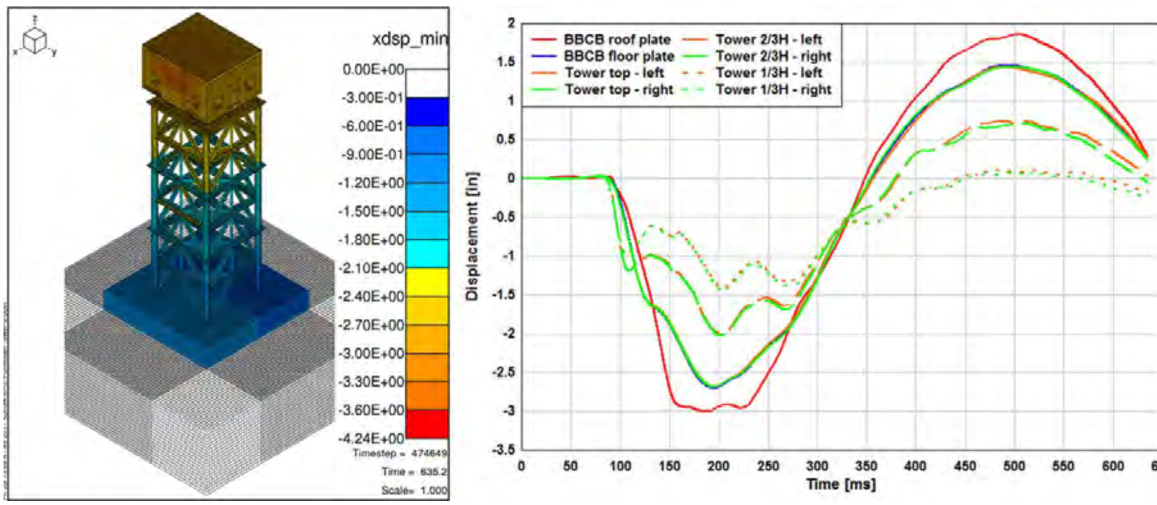

Figure 7. Response example: (left) Peak lateral displacement contours, (right) Lateral displacement time histories along the structure height.

As mentioned, local responses of the BBCB and support systems are also of interest, even if the global response is stable. Figure 8 shows two examples of the local responses of the BBCB wall panel facing a blast. Figure 8a shows the peak displacements of the panel into the BBCB interior space. The response is fairly uniform, showing a good response of the sandwich wall panel with windows and gun ports. Figure 8b shows plastic strains of the steel wall components. Plastic strains accumulate when metals are stressed past yield and so are indicators of inelasticity (but not necessarily imminent failure). These plastic strains are occurring in the window frames and angles connecting the wall plates. The plastic strain levels will indicate if the inelasticity is in the hardening regime of the steel response (before rupture) or softening regime (after rupture). Figure 8c also shows examples of steel inelasticity, this time in the support tower framing and connections. Again, inelasticity by itself does not equate to failure; the level of inelasticity is important.

One last interesting example of the local responses captured by the model is shown by the displacement time histories in Figure 9, showing the local response of one of the BBCB multi-plate wall panels. The red curve is the lateral displacement, normalized to the air gap thickness, of the BBCB outer wall panel on the blast face, the blue curve is the middle wall panel response, and the green curve is the inner wall panel response. Recall that the individual wall panels are separated by an air gap, and springs are used in the finite element model to model the interaction of the wall panels through the air gap. The

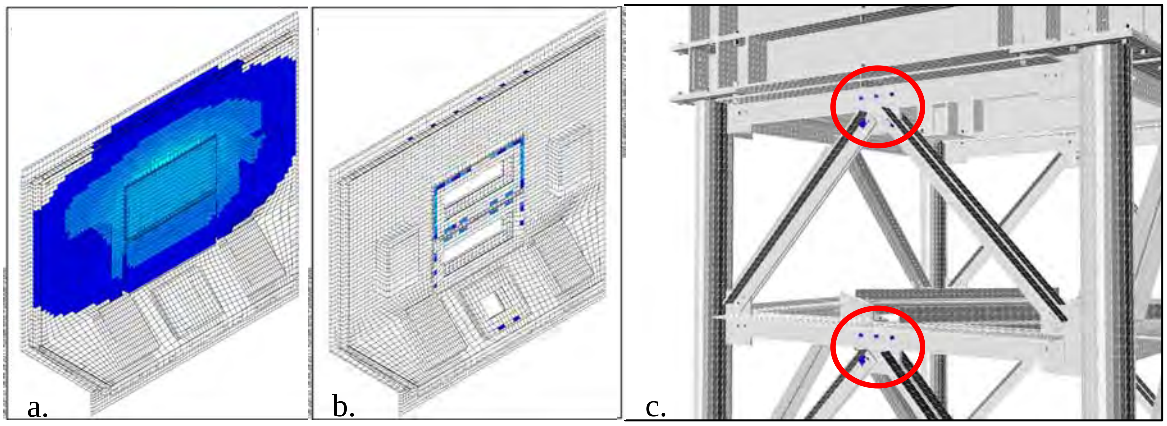

Figure 8. Response examples: Local response of blast-facing BBCB wall panel: (a) peak inwards displacement, (b) steel plastic straining; and (c) Indications of local inelastic responses in support framing

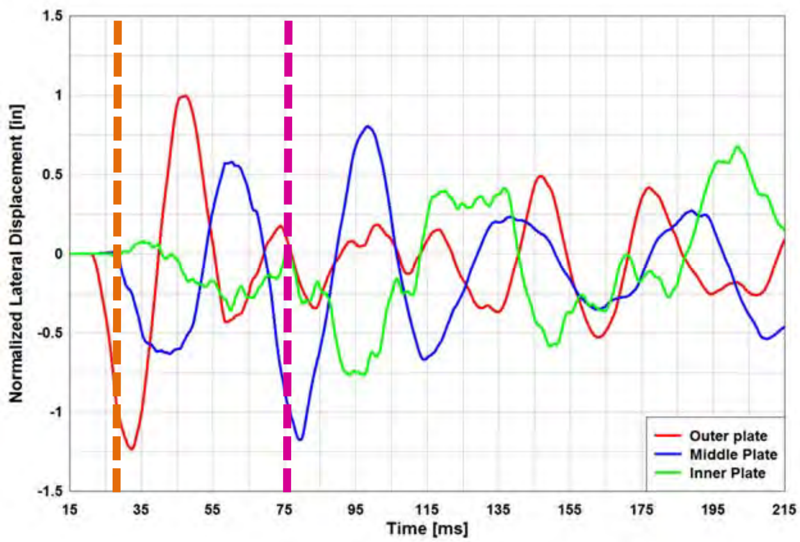

Figure 9. Response example: BBCB wall panel interaction.

time histories show the outer wall panel (red) responding first to the blast pressures. In this case the air gap closes at a normalized displacement of -1 in., and the outer panel closes that gap at about 30ms, denoted by the vertical dashed orange line. Closing the air gap means the outer panel impacts the middle panel, and indeed the middle panel (blue) begins displacing in the same direction at 30ms. The inner panel (green) has not yet been impacted, but it begins responding to vibrations transmitted through the perimeter connection angles tying the three plates together. Finally, at about 75ms the middle (blue) plate displaces enough to close the air gap between it and the inner plate (denoted by the vertical dashed purple line), impinges upon the inner plate (green), and pushes the inner plate to larger displacements than those due to vibration alone. These plate responses affect components such as windows, gun ports, and connections for these openings, and so accurately capturing the responses of the built-up BBCB wall panels is important. The importance of these panel displacements will also be further evident in the next section's discussion of human effects.

The purpose of the structural response calculations is to accurately capture the global and local responses of the BBCB and supporting structure to a blast event. Global response is obviously of upmost importance; the structure cannot collapse under blast loading and must continue to serve its purpose post-event. Local response is also very important because it gives an indication of the health of the structure and the balance between allowable structural response and local failure. Model fidelity to capture both global and local responses includes detailed modeling of the BBCB and support structure construction and connections, and the use of advanced analysis methods and material modeling. Neglecting the details put into these models and analyses can lead to an overly conservative, and costly, design. Blast is an extreme event and will push components and materials past their elastic limits, as shown in some of the response examples. In many cases this is an acceptable response, particularly for metals. Most metals have additional strength and ductility past yield. Utilizing this inelastic response regime allows yielding components to continue to perform during the blast event. Global stability and protection of the BBCB occupants must always be preserved, but allowing local nonlinearities to use components to their full capacities can result in design economies.

LETHALITY CALCULATIONS

The airblast and structural response calculations also provide sufficient data to estimate the lethality of the blast event to BBCB occupants. Two threats are posed to occupants by the blast event: overpressure inside the BBCB and accelerations induced by the structural response. A third threat, fragment impact, is negated by the ballistic protection afforded the occupants by the BBCB.

UFC 3-340-02 (Joint Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency, 5 December 2008) defines a method for calculating the pressure buildup in structures due to shock loads entering through openings. As described in the UFC, small openings will not allow the shock front to develop inside the structure, but these openings will allow for an increase in its ambient pressure in a time that is a function of the structure volume, opening area, and applied exterior pressure and duration. “Small” openings in a BBCB during a blast event may be provided by open gun ports, for example. The applied pressure and duration for the pressure buildup calculation is provided by the airblast calculation.

The rapid wall, floor, and roof panel movements due to the blast loads can also cause a pressure change inside the BBCB, and this pressure change would be added to the pressure buildup described in the previous paragraph to get the total pressure change inside the BBCB during the blast event. Displacements of the BBCB interior surfaces change the total volume of the enclosed space, and this volume change results in a pressure deviation from ambient. While phasing of the interior surface displacements may not be identical (i.e. the blast surface may reach peak displacement before the leeward surface), it is conservative to take the peak displacements of each interior surface when calculating the volume change and associated pressure change.

Velocity time histories recorded during the structural response analysis can be used to generate shock spectra plots at various locations inside the BBCB. The shock spectra plots can be used to estimate equipment fragility, and more importantly, potential human fragility due to acceleration of the BBCB during the blast event. Given the acceleration/frequency relationships defined by the graph, velocity and displacement for a single degree of freedom system can be determined with the relations

$$S_v = S_a \big/ \left(2\pi f\right) \tag{1}$$

$$S_d = S_v \big/ \left(2\pi f\right) \tag{2}$$

where f is the natural frequency of the equipment or occupant being investigated.

Studies have been done in the past to investigate human response to blast loading. Smith and Hetherington (Smith & Hetherington, 1994) summarize the findings of a few of these studies. Two locations in the human body most vulnerable to overpressure are the lungs and ears. Pressure-impulse curves have been generated to define thresholds and marginal survival percentages in blast environments. These thresholds can be compared to the calculated environment inside the BBCB to gage lethality. The shock spectra generated from the structural response data can be used to gage occupant response to the accelerations induced by the blast event.

CONCLUSION

Blast/Ballistic certified buildings (BBCB), placed at perimeters of restricted spaces, protect security personnel from external threats such as a vehicle-borne improvised explosive device (VBIED). The BBCB, whether ground-based or elevated by a support tower, must be robust enough to withstand the blast effects and provide protection to its inhabitants so that they can continue to provide site protection post-event. Given today's economic climate, the structure must also be efficient in design and construction.

While simplified methods exist for quantifying the airblast pressures on a target and the response of a single-degree-of-freedom representation of the structure to these pressures, the use of high-fidelity computational fluid mechanics and finite element calculations provide more accurate airblast and structural response results and deliver a wealth of useful information not delivered by simplified methods. CFD calculations provide threat and target-specific airblast pressure data that include the effects of the structure geometry and orientation, as well as pressure clearing around the target. Detailed nonlinear explicit finite element analyses provide accurate response predictions not only on a global scale but also on a local scale. Specific details include accurate representations of the structure construction and connections, geometry nonlinearity to capture large deformations of the structure or structural components, material nonlinearity to capture the responses of materials and components stressed past yield, and modeling to capture interactions of structural components during blast loading.

The data provided by the CFD and finite element analyses allows optimization of the structure design and information for estimating human response to the blast event. Modeling the geometric and material nonlinearities that may occur in a structure during a blast event allows the design to be optimized to yield but not fail, taking advantage of steel's post-yield hardening regime to deliver economizes to the design. The highly accurate CFD pressure calculations on all surfaces of the BBCB provide overpressure data that is used to calculate the interior overpressure during a blast event used to gage human lethality. Displacements calculated on the interior surfaces of the BBCB also provide overpressure data. Velocity time histories calculated on interior surfaces of the BBCB provide data for response spectra calculations, which in turn are also used to gage human lethality.

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