Structural Performance

performance issues relative to extreme events nsulated metal panels can provide a costeffective exterior cladding solution for a multitude of projects. However, the same mechanical characteristics that enhance the panels' flexural rigidity and provide weight savings also result in nonlinear response to loading. This is of particular interest in blast-resistant design, where components are often required to deform well beyond conventional serviceability limits.

In insulated metal panel products typically specified for exterior cladding applications, the interior and exterior panel faces are separated by a material such as mineral wool, polyisocyanurate foam, or other medium (*Figure 1*), which has two primary functions: serving as an insulation barrier to achieve a desired R-value; and increasing the moment of inertia, and thereby the flexural rigidity, without significantly increasing weight.

There are drawbacks, however, to this component geometry. A lightweight and relatively weak interior insulation material – commonly used

foam has an ultimate shear stress on the order of $f_{ve} = 30 \text{ psi} - \text{does}$ not allow for the assumption of plane cross-

By Jay S. Idriss, P.E., M.ASCE, Jack Fritz, P.E., M.ASCE and Jon A. Schmidt, P.E., SECB,

BSCP, M.ASCE

Dynamic Analysis of Insulated Metal Panels for Blast Effects

Jay S. Idriss (**jidriss@BakerRisk. com**) is a senior engineer on the Protective Structures Team at Baker Engineering and Risk Consultants, Inc., in San Antonio, Texas.

Jack Fritz (**jfritz@centria.com**) is a structural engineer at Centria, a major wall and roof system manufacturer with headquarters in Moon Township, Pennsylvania.

Jon A. Schmidt (**jschmid@ burnsmcd.com**) is an associate structural engineer and antiterrorism/blast consultant at Burns & McDonnell in Kansas City, Missouri.



sections remaining plane. Consequently, shear deflection cannot be neglected as in traditional bending analysis. Furthermore, the thin steel face sheets are prone to buckling prior to tension yielding of the full cross-section.

Nevertheless, with such an efficient cross-section geometry and insulation as an added bonus, this type of cladding solution is attractive to project engineers desiring weight and cost savings. Its proliferation has resulted in its specification on a variety of projects, and it has now found a common place among exterior walls systems designed for blast resistance. This article summarizes laboratory tests and simplified analytical methods that provide a fairly accurate methodology framework for the evaluation of these panels by structural engineers with blast-resistant design experience.



Figure 1. Typical insulated metal panel cross-section geometry. Courtesy of Centria Formawall.

Blast Resistant Component Analysis

Components specified for blast resistance are often assessed using a nonlinear dynamic singledegree-of-freedom (SDOF) methodology. The dynamic response of structural components to applied blast loads is determined by modeling them as simple SDOF systems (*Figure 2*). Structural components such as walls, windows, beams, doors, and panels will deform and respond dynamically when loaded with a blast pressure history p(t).

The SDOF model for each component is constructed using its dynamic structural properties – resistance function R(x), damping c, and mass m – so that the model will theoretically exhibit the same displacement history x(t) as the point of maximum deflection in the actual component. This displacement history is obtained with numerical integration techniques using a computer algorithm to solve the equation of motion of the SDOF system at discrete time steps.

For insulated metal panels, analytical resistance functions for use in SDOF modeling have typically been created by computing the gross elastic (and sometimes plastic) section properties and treating the components as beams, assuming that



Figure 2. Equivalent spring-mass SDOF system.





Figure 3. Static panel laboratory tests at Wilfred E. Baker Test Facility.

the full section yields and contributes to the moment capacity of the panel. The problem with this approach is that shear deformation and buckling are likely to occur during the panel response, such that traditional SDOF panel models routinely under-predict the response.

The derivation of an exact analytical function to model the relationship between the static resistance and deflection of an insulated metal panel is not trivial, as the function must take into account foam shear deformation and steel buckling modes, which occur at various phases of component response. Laboratory testing provides a practical way to derive such a function empirically and at full scale. Centria commissioned Baker Engineering and Risk Consultants (BakerRisk) to obtain the necessary data using its Formawall Dimension Series (3-inch T Series) product, and subsequently to develop a methodology for blast analysis and associated appropriate analytical response limits.

Experimental Approach

BakerRisk performed static tests in an apparatus similar to the one outlined in ASTM F2247-11, Standard Test Method for Metal Doors Used in Blast Resistant Applications (Equivalent Static Load Method). Bladders within the rigid box are designed to take the shape of the confined space within the apparatus, with the test specimen forming one side of the space. The apparatus uses a similar support fixture and test frame as that used for dynamic tests in the same facility's shock tube. The series of six tests subjected a variety of panel span configurations to increasing static load until failure, characterized as support disengagement. The collected data served as the basis for empirical resistance functions (Figure 3).

The response of an insulated metal panel can be characterized in several phases (*Figure* 4). The panels remain elastic and bonded throughout the cross-section under small displacements – less than one degree of support rotation when loaded statically – but the foam material then exhibits cracking and loss of composite action begins, followed by complete separation or delamination from the steel skins. As the stress increases in the steel skins, buckling occurs in the compressive skin. At this point, the foam cross-section near the supports is likely to be crushed. Secondary hinges then form in the panel skins, with membrane response occurring soon after, leading to eventual failure by support disengagement.

Analytical Approach

In blast analysis and design, SDOF methods are commonly used for their simplicity, solution speed, and reasonably accurate results. In many cases, the so-called *first peak* response is desired when evaluating a component's response to a blast load. A bilinear resistance function captures the initial "elastic" stiffness, while closely approximating the yield point at which the panel sections fail due to steel skin buckling or internal foam shear crushing. For common support conditions, BakerRisk derived and validated a methodology to determine key parameters of the bilinear resistance-deflection function; namely, the equivalent elastic stiffness K_e , the peak resistance R_{max} , the equivalent elastic deflection x_e , and the ultimate deflection x_{max} .

The equivalent elastic stiffness is approximated by bisecting the resistance curves associated with the panel shear stiffness and bending stiffness. This average stiffness term



Figure 4. Panel cross-section annotated with panel response phase descriptions.

Figure 5. Shock tube at Wilfred E. Baker Test Facility.

Insulated metal panel response categories.

Response Level	Response Description	Support Rotation Limit (deg)
Superficial	Possible partial internal component delamination with little to no damage evident upon exterior visual inspection	2
Low	Partial shear cracking and delamination of internal foam with no steel buckling	5
Medium	Minor steel buckling with minor permanent deflection	10
High	Steel buckling and significant permanent deflection	15
Blowout	Disengagement from support(s)	Varies – Dependent upon Support Bearing and Connection Capacities



Figure 6. Response examples, left to right: superficial and low, medium, and high.

is expressed mathematically as $K_e = 2/(1/K_v + 1/$ K_b). The computation of the shear stiffness parameter $K_v = 8h_cG_c/L^2$ (where h_c is the thickness of the foam core, G_c is the shear modulus of the foam (on the order of 300 psi), and L is the clear span length) reflects the shear deformations that occur due to damage of the inner foam layer of the panels, not typically observed or accounted for in general beam theory as previously mentioned. The bending stiffness parameter is computed as K_b = $C_k E_s I_s / L^4$ (where C_k is 76.8 for single (pinnedpinned) spans, 185 for end (pinned-fixed) spans, and 384 for intermediate (fixed-fixed) spans; E_s is the elastic modulus of the steel (typically 29,000,000 psi); $I_s = (h_p^3 - h_c^3)/12$ is the moment of inertia of the gross steel section; and h_p is the overall panel thickness).

The peak panel resistance is approximated by the insulated metal panel's shear resistance or bending resistance, whichever is greater. The shear resistance is computed as $R_y = C_{rv}h_c f_{vc}/L$ (where C_{rv} is 2 for single and intermediate spans, or 1.6 for end spans). It is important to note that the bending resistance $R_b = C_{rb}I_c \sigma_{cr}/h_p L^2$ depends on the buckling stress of the steel panel section, which is approximated by $\sigma_{cr} = 0.75^3 \sqrt{E_c G_c E_s}$ (where C_{rb} is 16 for single and end spans, or 24 for intermediate spans, and E_c is the elastic modulus of the foam (on the order of 500 psi). Once K_e and R_{max} have been computed, $x_e = R_{max}/K_e$. The ultimate deflection is associated with support disengagement, and thus only applies to single and end spans. It is approximated as $x_{max} = \sqrt{0.75(b_s/2)(L+b_s/2)}$ (where b_s is the width of the support).

Dynamic Shock Tube Testing and Analysis

BakerRisk performed blast testing on insulated metal panels using a shock tube (*Figure 5*) to validate the simplified analysis approach.

There were ten such tests on six specimens, including retests of panels exhibiting lower damage levels in order to maximize the amount of data gathered in the program. Observed specimen response ranged from superficial to high damage (Figure 6). The Table provides qualitative descriptions, along with quantitative support rotation limits established from the results of the test program. Note that these limits are higher than those published for "metal panels" in commonly used guidelines from the US Army Corps of Engineers (USACE) Protective Design Center and in ASCE/SEI Standard 59-11, Blast Protection of Buildings. This is because those published values are derived for bare corrugated components dependent upon the tension membrane reaction capacity of connections and supporting members.

The analytical methodology developed from static testing enabled the creation of SDOF models of the dynamic test specimens, excluding those that were pre-damaged from repeated testing. Loading these models with the measured pressure-time histories from the dynamic tests enabled comparison of the test data with the predicted response of the developed model, as well as the traditional gross section property model commonly used in the USACE SBEDS software program (*Figure* 7). Note that traditional analytical methods significantly under-predict response, primarily due to overestimation of the initial "elastic" panel stiffness.

Design Example

Consider a project where a 2.75-inch-thick insulated metal panel with 26-gage (0.019-inch) interior and exterior steel skins must be evaluated for blast resistance for an end span of 5 feet clear between supports that are 3 inches wide. The section properties are $h_p = 2.75$ inches, $h_c = 2.75 - 2(0.019) = 2.712$ inches, and $I_s = [(2.75)^3 - (2.712)^3]/12 = 0.071$ in⁴/in.

Shear stiffness $K_v = 8(2.712)(300)/$ $(60)^2 = 1.8$ psi/in, bending stiffness $K_b =$ $185(29,000,000)(0.071)/(60)^4 = 29 \text{ psi}/$ in, and equivalent elastic stiffness $K_e = 2/$ (1/1.8 + 1/29) = 3.4 psi/in. Shear resistance $R_v = 1.6(2.712)(30)/60 = 2.2$ psi, buckling stress $\sigma_{cr} = 0.75^3 \sqrt{(500)(300)(29,000,000)} =$ 12,000 psi, bending resistance $R_b = 16(0.071)$ $(12,000)/[2.75(60)^2] = 1.4$ psi, and thus peak resistance $R_{max} = 2.2$ psi. Equivalent elastic deflection $x_e = 2.2/3.4 = 0.65$ inch, and ultimate deflection $x_{max} = \sqrt{0.75(3/2)(60+3/2)} =$ 8.3 inches. For foam with a density of 2.6 pcf and steel with a density of 490 pcf, weight $w = (2.6)(2.712)/(12)^3 + (490)(2)(0.019)/(12)^3$ $(12)^3 = 0.015$ psi. Converting units, the mass for SDOF dynamic analysis is m = (0.015) $(1,000)^2/32.2/12 = 39 \text{ psi-ms}^2/\text{in}.$

A structural engineer can use these parameters (K_e , R_{max} , m) and the appropriate load and mass factors (K_L and K_M) in suitable dynamic analysis software – such as the General SDOF Program module of SBEDS – to calculate the peak panel deflection under any blast loading, convert it to the corresponding support rotation based on straight segments between hinge locations, and evaluate this against the limits in the Table. The acceptable response level is usually dictated by the required level of protection, with the panel treated as a secondary structural element. The maximum deflection must also be less than the ultimate deflection for panel disengagement (x_{max}) . Response of the panel in rebound - as well as rebound connection capacities - may need to be evaluated, as well, depending upon the applied load and specific project requirements.

Conclusion

Insulated metal panels are a common and cost-effective solution for exterior cladding, but their unique structural characteristics must be taken into account when analyzing their performance under high-magnitude dynamic loading, such as that produced by an explosion. This article provides the structural engineering community with a validated methodology for carrying out SDOF analysis of these products for blast effects, including typical material properties and appropriate response limits.





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