Simplified Method to Evaluate Shadow Box Pressure-Temperature Relationships

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Abstract

A common debate in the curtain wall industry is whether to vent or seal shadow box cavities. To address this, a simplified method is presented herein to assess the cavity pressure-temperature relationship within a sealed shadow box assembly. The goal is to provide a step-by-step approach that can be utilized by a wide audience of architects and designers since experimental testing and advanced computational analysis is not reasonably feasible for all projects and firms. It is important that venting shadow boxes is considered during design development so that it can be incorporated into project requirements and specifications, if appropriate.

A temperature rise can cause a considerable pressure build-up within a sealed air cavity if the deflection of the glass and metal panels cannot provide an adequate increase in volume. Previous research by others suggests the effect of temperature rise on cavity pressure is not significant due to deflection of the bounding elements, however, fail to correctly account for the nonlinear bending behavior of glass and metal panels. Significantly higher cavity pressures are determined when accounting for the nonlinear behavior of these elements.

Failure to account for high shadow box cavity pressures can have serious implications such as pressure build-up exceeding design wind pressure loads, long-duration loading on glass, back pan, and structural sealant, with potential rupture of air/vapor barriers. With a simplified method available, elevated pressures can be accounted for during design development to prevent unacceptable outcomes.

Introduction

For typical curtain walls, spandrel areas are primarily located at the floor slabs, dropped ceilings, and other structural and mechanical equipment to conceal them from exterior view.

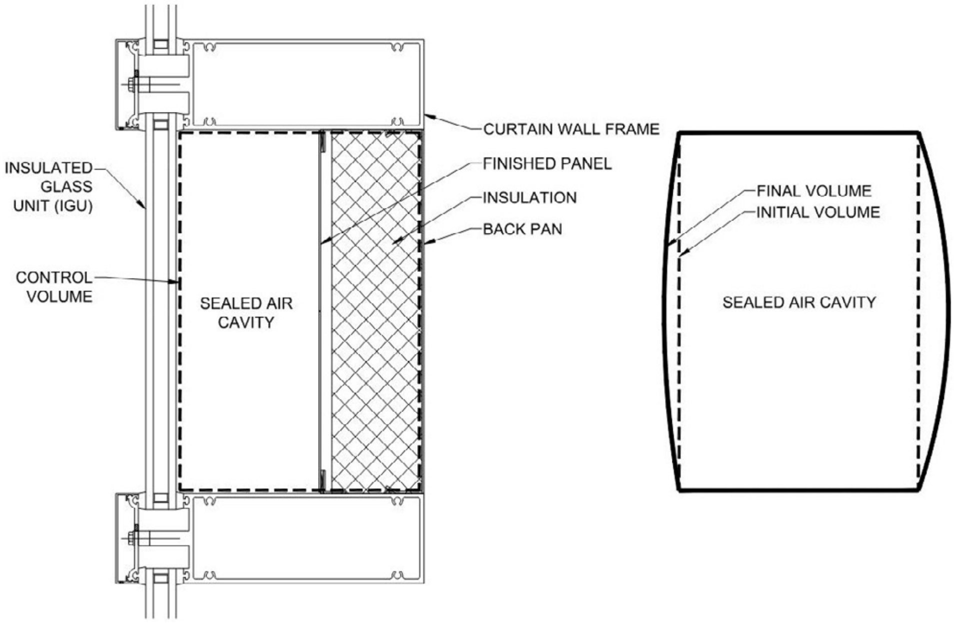

Figure 1. Typical composition and components of a shadow box assembly. The sealed air cavity control volume is indicated by the dashed outline. Note, the control volume assumes the insulation is porous, such as the case for mineral wool insulation.

For glazed spandrel areas, the glass can be vision glass (transparent) or opacified with ceramic frit, silicone, or back painted. The term shadow box relates only to the use of transparent glass on the front of a spandrel assembly since it allows natural light into the spandrel cavity to create a visual effect. The space between the vision glass and posterior opaque backing panels controls the depth perceived visually from the exterior. In most circumstances, this depth is controlled such that shadow box areas visually mimic the adjacent vision areas. The typical composition of components of a shadow box spandrel assembly is shown in Figure 1.

Shadow boxes can be sealed, pressure equalized, or fully vented. For a sealed shadow box, the cavity air is isolated in the spandrel assembly without any mass (air) exchange to the surroundings. For a pressure equalized shadow box, the pressure of the cavity air is regulated by small exterior-exposed openings. These openings are designed with the intent to equilibrate the spandrel cavity air pressure with the exterior air pressure. In reality, the pressure equalization is not instantaneous and occurs over a certain duration, depending on pressure and opening size. Fully vented shadow boxes have exterior exposed openings designed to circulate air between the shadow box cavity and exterior air. This ventilation is generally driven by natural convective processes. The intent is to increase the air exchange so that cavity temperature, condensation, and moisture accumulation is reduced. An exterior vented cavity is applicable to northern heating dominated climates whereas an interior vented cavity may be use for hot/humid (tropical) weather climates.

Since shadow box assemblies allow sun light into the spandrel cavities, they also allow for solar heating to occur. Regardless of the type of shadow box, this energy input can increase the temperature of the cavity air and shadow box components. This even occurs for fully ventilated assemblies since the air exchange is normally not high enough to result in appreciable cooling. Unique to sealed shadow boxes, an increase in cavity air temperature results in pressure buildup within the cavity.

A primary focus point of this paper to is to examine the pressure-temperature relationship in a sealed shadow box and discuss related design considerations. Although there are conditions where a sealed shadow box can be feasible (depending on climate, temperatures, and spandrel cavity design/geometry), ventilated or pressure equalized shadow boxes are typically best-

Model Inputs

Input the following variables using the units defined below:

- a – plate width, least plate dimension [in]
- b – plate length [in]
- d – cavity depth [in]
- E – modulus of elasticity of plate [psi]
- t – plate thickness [in]
- T_i – initial cavity temperature [Rankine]
- T_f – final effective cavity temperature [Rankine]
- V_i – initial cavity volume [in^3]
- p_i – initial cavity pressure [psi]
- p_{cav} – final cavity pressure [psi]

Approximate Plate Deflection

Solve for the outboard (W_1) and inboard (W_2) plate function:

$$W = K * t\sqrt{\frac{(a/2)^4}{E\,t^4}}$$

An insulated glass unit (IGU) can be approximated as a single plate using an effective thickness:

$$t_{eff} = \sqrt[3]{t_o^{\,3} + t_i^{\,3}}$$

Aspect Ratio (a/b)	K
0.4	2.5
0.5	2
0.6	1.5
0.7	1.25
0.8	1.0
1.0	0.8

Solve for Cavity Pressure

1. Calculate model coefficients

$$C_1 = \frac{4\,a\,b}{\pi^2} * (W_1 + W_2)$$

$$C_2 = V_i$$

$$C_3 = \frac{4\,a\,b}{\pi^2} * (W_1 + W_2) * p_i$$

$$C_4 = \frac{-p_i * V_i * T_f}{T_i} + V_i\,p_i$$

2. Input coefficients into cubic equation:

$$C_1\,q^3 + C_2\,q^2 + C_3\,q + C_4 = 0$$

Solve for variable "q" using graphing calculator or free website cubic equation solvers.

3. Solve for cavity pressure:

$$p_{cav} = q^2 \quad \text{[psi]}$$

$$p_{cav} = q^2 * 144 \quad \text{[psf]}$$

Figure 2. Simplified method to approximate sealed shadow box air cavity temperatures for a given effective/final temperature.

practice. This paper presents a simplified methodology to estimate the pressure in a sealed shadow box for a given temperature input so that the pressure-temperature relationship can be assessed early in the design process. With knowledge of this early on in the design phase, requirements can be included in the early design documents and specifications, basis of design, and owner's project requirements.

Pressure-Temperature Relationship for a Sealed Cavity

The air within a shadow box assembly is enclosed by glass on the exterior, a metal back pan on the interior, and the curtain wall frame on the sides. The glass is typically an insulated glass unit (IGU) but can also be a monolithic glass lite. When the temperature within the air cavity increases due to incident solar radiation, the IGU and back pan will deflect due to the expansion of the air. When these panels deflect, the volume of the air cavity increases. If the increase in volume is not adequate to accommodate the increase in temperature, a pressure buildup will occur.

Others have argued that the deflection of the glass and back pans increase the volume with temperature such that no appreciable pressure buildup occurs. However, the amount of deflection that would be required to maintain a low pressure is not possible. Actual panel deflection is nonlinear with respect to a uniform pressure load in which a panel becomes stiffer as it deflects due to membrane action. When correctly accounting for the nonlinear behavior of the glass and back pan, significantly higher cavity pressures are realized.

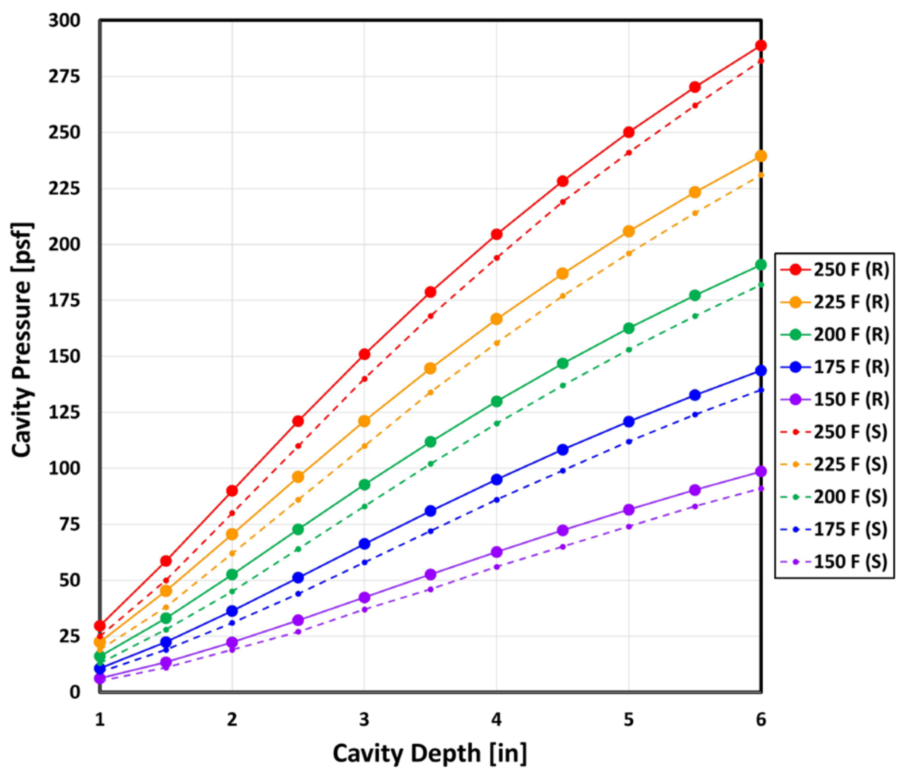

Figure 3. Comparison of cavity pressures for an example sealed shadow box assembly. The cavity pressure outputs are shown based on the regression-based (R) approach and the simplified method (S), as described in Figure 2. The temperature listed is the final/effective temperature of the shadow box air cavity. The example case considers a 3'x5' shadow box with an IGU (1/4"-1/2" air-1/4") and 1/16" steel back pan. An initial cavity temperature of 70 degrees Fahrenheit was assumed.

A fully sealed shadow box assembly can be mathematically modeled as an enclosed rectangular control volume with deformable boundaries at two opposing sides (outboard and inboard faces). The control volume is assumed to be filled with air without any air exchange with the exterior or interior environments. Therefore, the air in the control volume is bound to the thermodynamic equation of state known as the Ideal Gas Law. Although air is a mixture of gases, it can be modeled as an ideal mixture and follows the relationship defined by the Ideal Gas Law within reasonable tolerances for the temperatures and pressures being considered.

To determine the pressure within a shadow box, finite-element analysis (FEA) software and nonlinear regression (curve-fitting) was used to develop a pressure-deflection function for plates with different thicknesses, sizes, and mechanical properties. The function was then used in an algorithm to solve for the shadow box cavity pressure. This process requires knowledge of FEA software and additional mathematical modeling that may not be available to all architects, designers, and firms due to project budgets and schedule. To simplify the process, we approximated the nonlinear plate behavior by an algebraic plate function that is incorporated into a step-by-step algorithm. Model constants related to plate aspect ratio were developed so that FEA is not required. Coefficients are inputted into a cubic equation which is then solved to determine the cavity pressure. This method is able to be used by a wider range of users since no computer or mathematical modeling is required. The cubic equation can be solved easily with a graphing calculator or free online website solvers. This step-by-step process is shown in Figure 2.

A comparison of the cavity pressure outputs between the regression-based (R) approach and the simplified method (S) are shown in Figure 3 for various cavity depths. Although the simplified method results in cavity pressures approximately 3 to 10 psf less than the regression-based method, the difference is insignificant considering the order of magnitude of pressures being considered. As shown in the figure, a larger cavity depth/initial volume results in higher cavity pressures since the percent increase in volume (due to panel deflection) is lower. For shadow boxes with a large cavity depth, a relatively small increase in temperature can result in a high cavity pressure. This is significant for shadow boxes since they typically have larger cavity depths in order to provide the desired aesthetic.

Effective Temperature

The in-service temperatures at the center of the shadow box cavity can be extreme and have been measured (both in-service and experimentally) to exceed 200 degrees Fahrenheit. To computationally analyze design shadow box temperatures, LBNL WINDOW software solves for surface temperatures based on energy balance methods outlined in ISO 15099. From this, center-of-shadow box air temperatures can be conservatively approximated for various solar load inputs based on geographical location, elevation, and incidence. However, the temperature in the shadow box varies and this center-of-shadow box temperature does not fully dictate the cavity pressure.

As illustrated in Figure 4, the cavity air temperature near the frame (zone 2) and within the porous insulation (zone 3) will be lower than the center-of-shadow box air temperature (zone 1). Therefore, the shadow box air cavity will have constant pressure throughout the control volume with local variations of density and temperature. The center-of-shadow box temperatures calculated by LBNL WINDOW are conservative and a reduced, effective temperature is more appropriate for shadow box cavity pressure calculations. The effective temperature can be approximated by a volume-weighted average of the various temperature within the shadow box, which can be conservatively approximated using LBNL THERM and WINDOW software. The effective temperature is highly dependent on the insulation thickness since the air within the porous insulation experiences a high temperature gradient in which air near the outboard side is closer to the cavity air temperature and the air near the inboard side is closer to the interior temperature.

Spandrel Glass and Spandrel Panels

Shadow boxes are the focus of this paper as they typically represent the highest in-service temperatures for sealed air cavities on exterior walls. However, spandrel areas using spandrel glass and spandrel panels are also common and should also be considered for potential pressure build-up within the assembly.

Spandrel insulated glass units with a ceramic frit coating on the #3 or #4 surface are often installed in spandrel box assemblies. The ceramic frit coating absorbs a larger percentage of the incident solar radiation, therefore, reduces the solar radiation incident on the interior components within the spandrel box assembly. Heat transfer from the frit to the exterior is impeded by the air space and low-e coatings. Therefore, spandrel glass used in sealed assemblies can result in extreme temperatures. However, air cavity temperatures are typically less than those of shadow boxes under the same climatic and design conditions. Although temperatures are less, spandrel box assemblies can experience high enough temperatures to create a pressure build-up if the assembly is fully sealed.

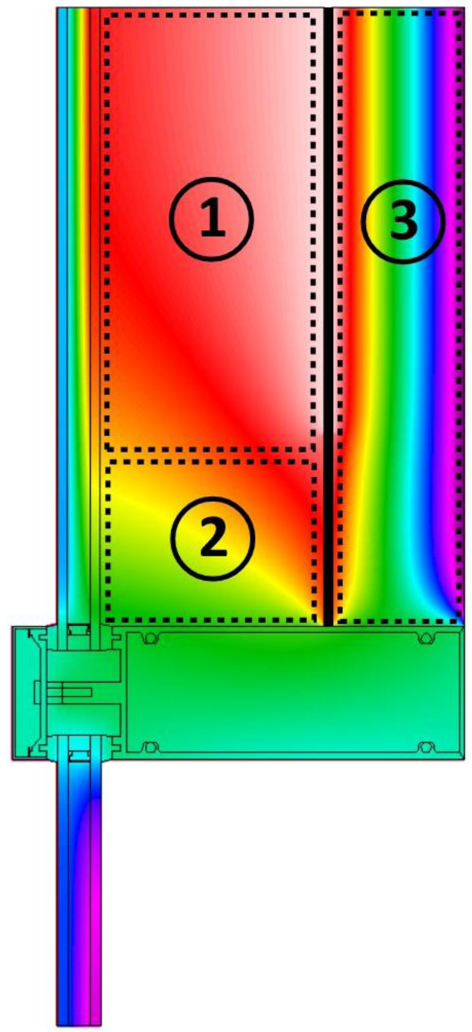

Figure 4. Approximate 2D temperature gradient within a shadow box assembly in summertime and solar load conditions. Zone 1 represents the center of shadow box temperature that is typically approximated by LBNL Window. Zone 2 represents reduced temperatures due to cooling by the frame. Zone 3 represents temperature gradient that exists due to mineral wool insulation. As noted, the effective temperature to determine cavity pressure can be approximated by a volume-weighted temperature of the three zones.

Spandrel areas can also be infilled with opaque metal panels, which do not experience as extreme temperatures as shadow and spandrel box assemblies. Like the spandrel IGU, the opaque metal panel absorbs the incident solar radiation, however, due to the lack of an insulating air space, heat is able to be transferred to the exterior resulting in relatively lower air cavity temperatures. Figure 5 demonstrates temperatures for shadow box, spandrel glass, and spandrel panels assemblies computed for 100% solar incidence with LBNL WINDOW software. Note, insulation thickness and air space was kept constant for comparison only. For spandrel glass and panel conditions, a large air space would not be required for aesthetics since the interior is not visible.

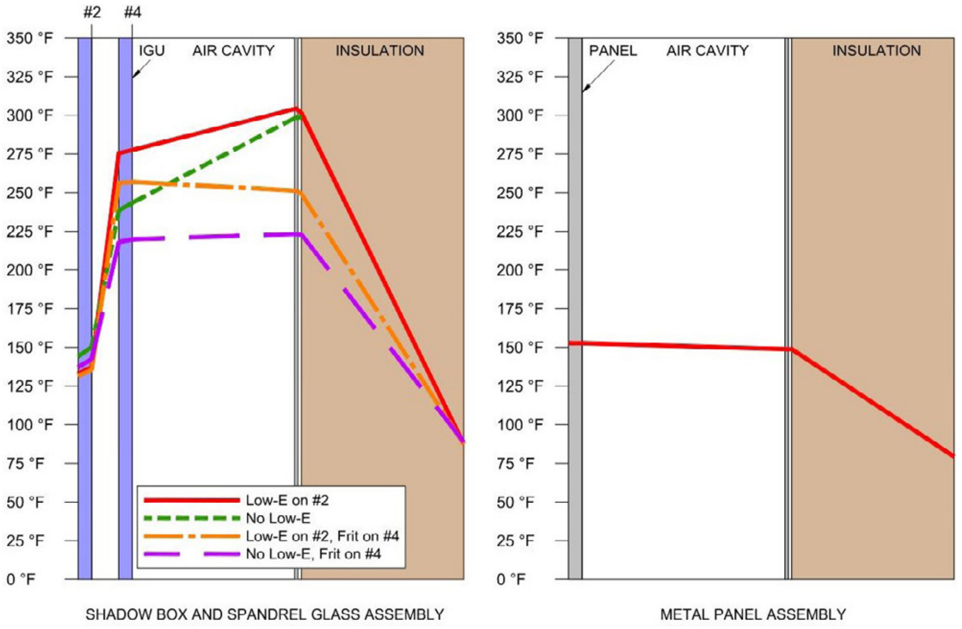

Figure 5. 1D Temperature approximation for shadow box, spandrel glass, and spandrel panel conditions. The effect of low-e coatings and opacifiers (i.e. frit) on temperature is included for comparison. Temperatures shown are computed from LBNL WINDOW software assuming 100% solar incidence and standard solar load.

Design Considerations

The impact of pressure rise within a sealed shadow box or spandrel box assembly is often overlooked and can lead to underperformance and failure of one or more components. Under certain circumstances, the pressure within a sealed shadow box can be significant and may even exceed the design wind pressure load. With such high pressures, it is likely that air/vapor barriers rupture as the panels and joints become distressed under load. Once this occurs, the pressure within the shadow box generally equalizes with the interior environment. This is especially likely for shadow boxes that do not contain back pans in which foil faced insulation (if properly installed) would be pushed from the shadow box assembly due to the pressure build-up. Also, foiled faced air-vapor barriers are unable to be installed in a manner to provide this air-vapor barrier function long-term as they often become damaged and/or are not fully sealed. For assemblies with back pans, noise due to the flexing of back pans under pressure have been reported by occupants. Also, continuous flexure of the IGU can result in wear on insulating seals. Potential for glass breakage to occur should be assessed with consideration to the pressure build-up within the cavity as well as thermal stress at the glass perimeter.

IGUs glazed in shadow box/spandrel box assemblies can be secured with structural silicone glazing (SSG). The size of the SSG bite is typically sized based on published sealant strength for wind and live loads. These loads are of shorter duration in which a design wind load is related to a 3-second gust duration. As the duration of the load increases, the allowable strength of the SSG decreases significantly. For sealed shadow box assemblies, the peak temperature/pressure build-up may occur for a few hours. Therefore, the SSG joint design should also consider the anticipated shadow box pressure and duration as this may govern over design wind load.

To mitigate nearly all performance issues often attributed to shadow and spandrel box design, it is our opinion that these assemblies should always be pressure equalized to the exterior for cold climates. Despite the PE/vent holes, dirt-build up on the inside face of the IGU is minimized with use of very small openings or high PPI baffles. Also, appropriate use of pressure equalization or venting for different installations and climates can minimize the potential for internal condensation and resulting dust accumulation.

As outlined in this paper, for sealed conditions, the back pan should be designed for appropriate design pressures due to temperature related pressure build-up and load sharing from wind loading. For a pressure-equalized or vented configuration, the back pan experiences a reduced load due to wind pressures not fully equilibrating the air cavity over the short wind load duration. However, for all cases, back pans are recommended to be used as they provide a robust vapor barrier. The back pan should be designed and stiffened as required by the anticipated in-service pressures. Note, stiffening the back pan will result in reduced deflection. For a sealed condition, this increases the pressure build-up in the cavity and the load on the IGU. For a PE/vented condition, stiffening the back pan will not increase the load on the IGU for temperature-induced pressure loads.

Venting shadow/spandrel boxes may expose the interior cavity to colder temperatures during wintertime. At times the inboard side of the thermal break is exposed to the shadow box cavity in which this would cause a thermal bridge. To mitigate this for spandrel glass areas, insulation can be installed at the perimeter of the shadow box along the curtain wall frame to increase frame temperatures during the winter and decrease frame temperatures during the summer. Likewise, the finished panel can be attached to the frame with a thermal break. It is recommended that the finished panel is not sealed at the perimeter to prevent compartmentation and to allow for drainage of any condensation that forms within the insulation.

There are many design considerations for shadow box and spandrel cavity design, and only a few topics are discussed herein. Discussing the design of shadow boxes in full is outside the scope of this paper. Previous research has measured shadow box temperatures both in-service and experimentally, however, to our knowledge, there has not been substantial experimentation to measure pressures within sealed shadow boxes. Further experimental testing along with development of industry standards related to shadow box design is encouraged so that a design consensus can be achieved in the future.

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