LOAD SHARING AND SPACER FLEXIBILITY IN DOUBLE PANE AND TRIPLE PANE INSULATING GLASS UNITS

A Thesis

by

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ABSTRACT

Insulating glass (IG) is comprised of two plates of glass that lie close to one another without touching. The plates are separated by a sealed gas space that consists of a spacer material that surrounds the perimeter of each plate. This spacer does not allow gas flow into or out of the IG unit. IG must consist of at least two plates of glass, but can be expanded to three plates of glass where there would be two sealed gas spaces. As a result of the configuration of IG units, the load that is distributed between the plates will vary based on the properties of the glass, the initial conditions of the unit, and the properties of the spacer material.

It has long been understood that the load sharing between double pane IG units can be influenced by different factors in the unit. These factors include the thickness of the plates, temperature variations in the sealed gas space, and atmospheric pressure differences between the sealed gas space and the current atmospheric pressure.

Computer software was used to write a program that accurately modeled existing experimental data on tests completed for double pane IG units. When accurate results were obtained, a portion of the research was used to focus on flexibility in the spacer material transferring a portion of the load through the unit.

A triple pane IG model was developed to evaluate the effects of extreme pressure drops in a hurricane as well as gas space temperature variations. Spacer

flexibility was incorporated into this model to see its influence on load sharing between the plates of glass. The triple pane IG unit's plates were sized and then analyzed to see how the pressure drop and temperature variation influenced the original design.

DEDICATION

To the writer's wife, Sarah for her continuous support, love, and companionship through many challenges in life.

To the writer's daughter Emma for her continuous love and affection.

To the writer's parents, both biological and in law for their continuous love and guidance.

To Dr. W. Lynn Beason for his influence and knowledge in academics and structural engineering.

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CHAPTER I

INTRODUCTION

Windows are one of the primary elements that control the energy conservation behavior of the building envelope. This is the case because it is not possible to introduce common insulation materials into the window system without destroying the primary purpose of the window, which is to maintain the structural integrity of the wall system while allowing visibility. As a result of the inherent energy inefficiency of windows, a large amount of energy flows outward in the winter and inward in the summer. With energy costs always rising, the demand to create more efficient windows has led glass manufactures to experiment with alternative solutions. Over time, windows have evolved from single pane to double pane insulating glass (IG) units. Almost all windows produced today incorporate at least double pane IG. More recently, triple pane IG units are being used, particularly in extreme climates.

A double pane IG unit is fabricated with two parallel glass plates of equal size area. The plates are connected at the edges with a spacer of constant thickness. The separation, created by the spacer between the two plates, is typically on the order of 1/8 in. to 1/2 in. The space between these two plates of glass is known as the gas space. In early IG units, the gas space was typically filled with desiccated air. However, manufactures have discovered that other gas mixes that contain inert gases, such as argon or krypton, provide additional energy savings. The use of double pane IG units significantly reduces energy costs when compared with single pane windows.

Recently, triple pane IG units have been produced in an effort to provide more energy efficiency than double pane IG units. The primary difference between double pane and triple pane IG units is that a triple pane IG unit has an extra glass plate and an extra spacer. The three plates that make up the triple pane IG unit are connected at the edges with two spacers, introducing a second gas space. The perimeter spacers are typically sized to create two gas spaces of equal thickness. Triple pane IG units provide increased performance when compared to windows that incorporated either single pane glass or double pane IG units. Windows that incorporate triple pane IG units are beginning to become more common for use in homes and commercial applications.

As previously stated, the primary purpose of the window is to maintain the structural integrity of the wall system. This means that the window must be able to resist a specified lateral load that is representative of a typical wind load. Consequently there are two primary concerns involved in the design of windows: energy efficiency and load resistance. At this point in time, energy efficiency is the primary criteria being used to select the type of glass in a window (i.e. single pane, double pane, or triple pane). However, it is still necessary to be able to properly select the thickness of glass required to resist the specified wind load. To accomplish this, it is imperative to have reasonable methods to estimate the load sharing properties of both double pane and triple pane IG windows. Estimating the load sharing properties of insulating glass is the primary topic of the research presented herein.

Due to high usage, an understanding into the load sharing relationship between the plates of glass in a double pane IG unit was developed by Beason (1986b) and Vallabhan (1986). The original double pane IG unit load sharing relationship developed by Beason (1986b) assumed that the spacer experienced no significant deformation when loaded. Although there is an understanding into how the load is shared between the two plates of glass in a double pane IG unit, there still is no palpable knowledge into how the properties of the spacer affect the performance of the unit. There is also very limited understanding of what the structural relationship is between the three plates of glass in a triple pane IG unit.

The first objective of the research presented herein is to modify the original double pane IG unit load sharing analysis developed by Beason (1986b) to account for spacer flexibility. Beasons test data will be used to evaluate the results and estimate the spacer flexibility for a typical silicone spacer system. The second objective of the research is to develop an understanding into the load sharing relationship between each plate of glass in a triple pane IG unit. The double pane IG load sharing analysis with spacer flexibility will be reworked to accommodate a triple pane IG unit with flexible spacers.

Chapter II of this thesis presents the problem statement. The problem statement outlines the topics that will be analyzed regarding spacer flexibility and triple pane IG. Chapter III presents the history of IG and any available previous research used to define the properties of IG. Chapter IV is focused on the double pane IG unit analysis with flexible spacers. This includes the process of building a program to model double pane IG that will analyze spacer flexibility. It also includes the results presented on double pane IG. Chapter V is focused on the development of a triple pane IG unit with flexible spacers. Included in this chapter is the building of a program that can handle a triple pane IG unit, and the results obtained from this program. Lastly Chapter VI presents conclusions that can be taken from the research conducted herein.

CHAPTER II

PROBLEM STATEMENT

Double pane insulating glass (IG) units consist of two glass plates of equal size placed parallel to one another, and bonded together by a continuous spacer around the perimeter. The void between these plates is known as the gas space, and is sealed so that gas cannot enter into or out of it Fig. 2-1. A triple pane IG unit consists of three plates of glass placed parallel to one another with two spacers separating each plate, creating two sealed gas spaces Fig. 2-2. There is theoretically an unlimited possibility for the number of plates of glass that could be combined in an IG unit, but space and weight restrictions usually prohibit the unit from anything larger than a triple pane IG unit.

As previously stated, the two major design considerations for IG units are energy conservation properties and wind load resistance. The research presented herein is focused on the wind load resistance of the IG.

IG is typically installed within a window frame, providing lateral support for all four edges of the IG unit. When the IG unit is subjected to wind load, the outer glass plate deflects into the first gas space. This causes the pressure of the gas space to increase and load is transferred to the next plate. If there is a third glass plate in the IG unit, a similar interaction happens between it and the second glass plate. Ultimately, the total window load that is placed on the IG unit will be distributed between each plate within the IG unit. Analyses that are used to determine the exact

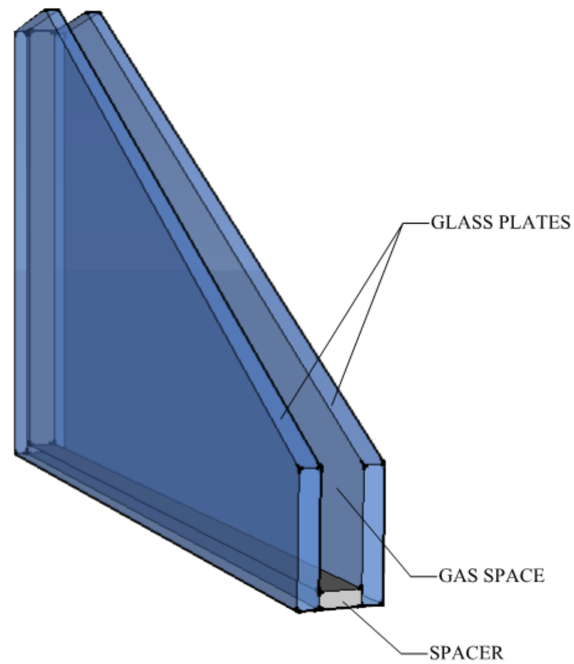

FIG. 2 - 1 Corner cut of a double pane insulating glass unit

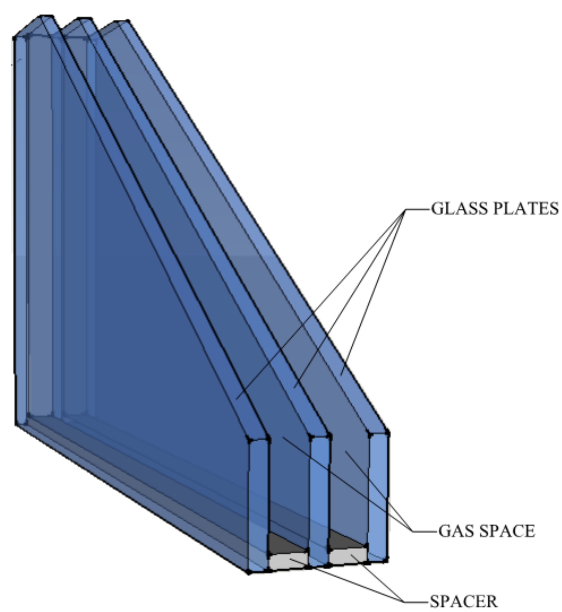

FIG. 2 - 2 Corner cut of a triple pane insulating glass unit

manner in which the load is apportioned to each of the plates in the IG unit are called load sharing analyses. The manner in which the load is distributed between the various plates is dependent on many factors, the most important of these being the glass plate geometries and the spacer stiffnesses.

Research has been conducted by Beason (1986b) to understand the load sharing relationship of double pane IG units. This initial work did not account for the possible effects of spacer flexibility. In addition there is little information available about the load sharing relationship between triple pane IG units. This is partially due to the fact that triple pane IG has only recently begun to gain popularity for residential use, while double pane IG has been in service for many years.

The purpose of the research presented herein is to modify the original double pane IG load sharing model developed by Beason (1986b) to include spacer flexibility. This modification serves to develop a better understanding of the IG load sharing analyses, and more accurately predict how the wind load is transferred between the individual plates. In addition, this improved load sharing model is altered to handle triple pane IG units with flexible spacers. This new model will be used to evaluate the effect of spacer flexibility in triple pane IG units. Analysis will also be done to accurately size the glass plates in three different common window types. These units will then be evaluated after they are exposed to an atmospheric pressure drop from a hurricane, as well as when the gas space temperature is varied from low values to high values.

These improved load sharing models are used to determine how different factors affect the load sharing relationship in double pane IG units with flexible spacers, and triple pane IG units with flexible spacers. Specific areas of study include the effects of atmospheric pressure change, temperature change, variations in plate thickness, deviations in lateral loads, and disparities in gas space thickness.

CHAPTER III

PREVIOUS RESEARCH

Over the past century, windows have evolved from single pane to double pane to more recently, triple pane Insulating Glass (IG) units. While there is currently an accepted understanding into the load sharing relationship of double pane IG units, there is little information available on the load sharing relationships between triple pane IG units.

This chapter focuses on the beginnings of IG, and how the material evolved over the years. In addition, this section presents a general review of load sharing analyses that have already been developed.

HISTORY OF INSULATING GLASS UNITS

The first patent for double pane IG was awarded in August 1865 to Thomas D. Stetson, an engineer from New York. Stetson sought to rectify the most vulnerable part of any building, the windows. Others had previously proposed a solution of putting two pieces of glass next to each other without a spacer, similar to laminated glass. The problem with these units, however, was that they did not have the thermal properties offered by IG. Stetson proposed that two panes of glass be placed next to each other, kept separate by a distance. This left an exposed space between the two sheets of glass which he then sealed together with a spacer. For the spacer he proposed enclosing a wood stick in a putty type material. He noted that this type of spacer configuration acted similar to a spring in that it would contract when a uniform loading was present on one of the plates of glass. Although this is discussed in his patent, no experimental calculations were included. This is also the only reference to a spacer material acting in a spring like manner that the author was able to find in any of the readings conducted. Stetson did not consider the spacer thickness to be of much importance.

Stetson's initial concept was not used for commercial purposes until Charles D. Haven made revisions, pointing out the weaknesses of the initial design and improving the areas that were flawed. Haven recognized that the units were not functional in use, his main concern with double pane IG being the space between the two sheets of glass. If this area were to be compromised by allowing water or oils into it, the entire unit would be ruined. This is because these foreign elements have the potential to cause staining and marks on the inner portions of the glass, rendering it necessary to take the unit apart to clean. In this event it would not be cost effective or even possible to refurbish.

Haven noted that in double pane IG, the two plates of glass are exposed to completely different conditions. In comparison to the inner plate, the outer plate would experience rapid changes in temperature. This created a scenario where one of the plates of glass expanded or contracted more than the other plate, creating strain on the spacer material holding the sheets together. He learned that if a spacer was too rigid, the stresses on the glass would be too high. If the stress becomes too high, a crack would form from the corner and protrude toward the center. However, this would only occur if the unit was completely sealed. This means that if a seal were to be created between the rigid spacer and the glass, the double pane IG unit would fail due to glass breakage. If a seal could not be obtained, then outside material would be allowed to seep into the double pane IG unit and stain or fog the interior glass of the unit.

Haven developed a flexible, yieldable spacer material that he produced from a rubber composition. This flexible spacer was beneficial because it provided some elasticity when the glass expanded and contracted. The flexible spacer created a spring effect, and absorbed some of the load.

In February of 1936 Haven filed a patent for this method of producing double pane IG units. From his patent he was able to commercially produce double pane IG under the umbrella of Thermopane. The spacer used in the production of Thermopane was made of smooth rubber sheeting cut into strips and laminated together. However this was not a continuous tight connection. When the unit was exposed to fluctuating temperatures, the glass sheets had a tendency to move. If any separation of the spacer and the glass were to occur, this type of bond would continually strip off and become completely separated. To solve this problem Haven developed a spacer with an interrupted bond. To create this, he roughened the rubber so that when it was attached to the glass it did not have two smooth surfaces connecting together. As the surface was not continuously connected, the next surface would not likely separate after the first section failed. While parts of the spacer may break down, as a whole it would keep it from having any areas where the seal was completely broken.

MODERN INSULATING GLASS UNITS

As previously mentioned by Haven, one of the main concerns with IG is that the space between the glass needs to remain completely dry. The small amount of gas that can be held in the interior of a unit will not take much moisture to saturate. Due to this fact a revised spacer design was developed by IG manufacturers concealing a desiccant next to or inside the spacer absorbing any moisture trapped inside the IG unit as shown in Fig 3-1.

In some cases a capillary tube is incorporated into the IG unit design when the unit is manufactured, so that the atmospheric pressure can be equalized at the time of installation. When the IG unit is mounted into a building, this tube is typically pinched off creating a sealed gas space. In these situations it is very important that the desiccant be able to prevent moisture from entering the unit and causing internal damage.

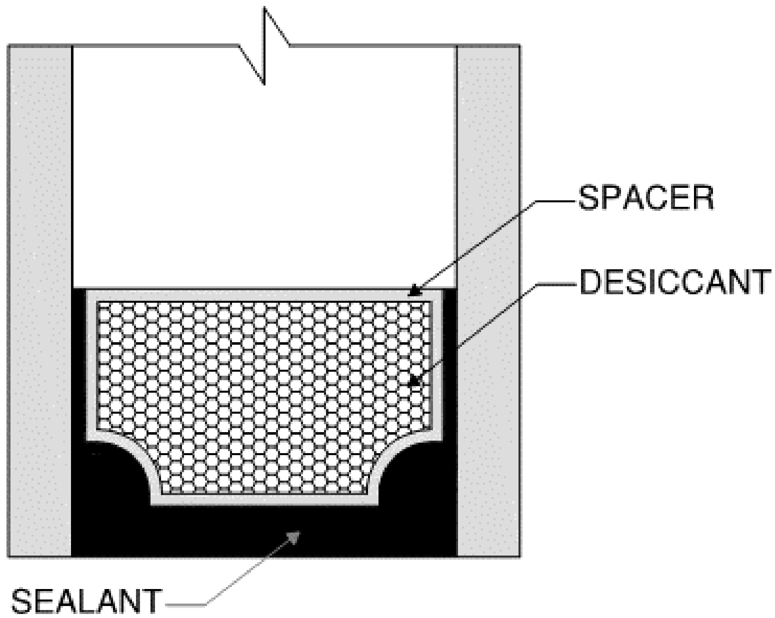

FIG. 3 - 1 Desiccant in double pane insulating glass unit

Early on it was recognized that the glass plates in sealed double pane IG units share the applied lateral load. Most design procedures in the seventies incorporated a factor that was used to estimate the strength of the insulated glass based on the strength of one of the single glass plates in the double pane IG unit. Since most IG units employed balanced glass, the strength of a single glass plate was determined from conventional glass thickness charts. This value was then multiplied by the IG strength factor of 1.5 (PPG 101A 1970, LOF Standard, UBC 1976, UBC 1982). While this produced conservative results, it was not based on solid analytical procedures.

LOAD SHARING ANALYSES FOR IG UNITS

Solvason (1974) developed the first load sharing model. His model took into consideration temperature and barometric pressure changes in addition to glass thickness and thickness of the spacer. This system assumed a rigid spacer. The load sharing model used a linear elastic approach and concluded that spacer thickness had a significant influence on the load shared by each plate. This produced results that were reliable for small deflections of the glass plates, but with large deflections the plates act nonlinearly.

Beason (1986b) used an iterative process to develop a sealed double pane IG load sharing model exposed to a uniform lateral load. Using a rigid spacer, this research evaluated changes in gas space thickness and different plate thicknesses. In addition, this model could accommodate fluctuations in gas space temperature and atmospheric pressure. Results were obtained by simultaneously solving equilibrium equations and keeping gas space compatibility relationships. This analysis made an assumption that the gas inside the unit behaves as an ideal gas. It used nonlinear plate analysis by Vallabhan and Wang (1981) to correlate the aspect ratio of the window with a nondimensional lateral load. Another assumption made was the deflection of a single plate in the double pane IG unit would behave as a single plate.

This procedure led to the conclusion that if no additional factors were present on a double pane IG unit, the load shared would be relatively equal. However load sharing could fluctuate considerably if there were variations in the plate thickness, gas space temperature, or atmospheric pressure.

Vallabhan (1986) used the finite difference method to solve the von Karman nonlinear plate equations using a code developed by Vallabhan and Wang (1981). This procedure used the ideal gas law along with nondimensional loads and nondimensional volumes to iteratively balance the deflection of the two plates in a double pane IG unit. This produced similar results to Beason (1986b) and it included variations in glass plate thickness and gas space temperature. It did not, however, include atmospheric pressure changes or spacer flexibility.

Norville (2011) presented a triple pane IG load sharing model where he used nondimensional volume verses nondimensional pressure differences between the three plates of glass. Norville's research is focused primarily on the differences between ASTM values and his load sharing model. This research is limited to load sharing and does not take temperature change, atmospheric pressure variations, or spacer flexibility into consideration. The results of this research are presented later in this thesis, showing a side by side comparison of the results reported in this research versus what was uncovered in the current research.

CHAPTER IV

DOUBLE PANE INSULATING GLASS

Double pane insulating Glass (IG) is an alternative to a single pane (monolithic) glass system, where more than one sheet of glass is used in a window unit. In double pane IG there are two sheets of glass as demonstrated in Fig 4-1. The unit consists of an inner plate and an outer plate, which are placed close together with a void between them. This void is known as the gas space, and it is confined by a spacer that goes around the perimeter of each plate. This spacer creates a seal to ensure that gas and moisture are kept from entering or exiting the double pane IG unit. There is typically a desiccant inside the spacer to remove any humidity that may have been trapped in the gas during manufacturing.

When the unit is sealed, the pressure inside the gas space is the same as the atmospheric pressure outside the unit. This means that there is no load acting on either the inside or the outside plate of glass at the point of manufacturing. When the double pane IG unit is installed in a building, the pressure in the location could be different from where it was produced. To equalize the gas space with the existing conditions, there is typically a capillary tube in the unit. This tube will allow the pressure to neutralize so that the unit does not have any load at the time of installation. The research presented herein will be conducted with a sealed gas space.

FIG. 4 - 1 Typical double pane insulating glass cross-section

When the unit is exposed to a uniform pressure on the outer plate, it causes that plate to deflect into the unit. Consequently, this reduces the size of the gas space causing an increase in gas space pressure. This increase will cause the inner plate to deflect and begin to take a portion of the load. As the inner plate deflects, the gas space pressure will reduce until the unit is able to maintain equilibrium. This process is known as load sharing. The amount of load that each pane of glass takes is dependent on the properties of each plate of glass along with atmospheric pressure and gas space temperature.

Changes in atmospheric pressure or gas space temperature create a much different load sharing scenario. When a sealed unit is installed, any deviation in atmospheric pressure or gas space temperature will create a load on the plates. An example would be if the window were installed and outside forces caused atmospheric pressure to reduce. The plates of glass would bulge outward, as shown in Fig. 4-2. An increase in gas space temperature can also cause this to occur. The opposite effect will occur if there is an increase in atmospheric pressure or a decrease in gas space temperature.

FIG. 4 - 2 Idealized double pane insulating glass unit with low atmospheric pressure

THEORETICAL DOUBLE PANE IG LOAD SHARING ANALYSIS

The double pane IG load sharing analysis, which uses a theoretical evaluation to model the structural performance of rectangular double pane IG units, was established by Beason (1986b). For this research, a Matlab model was built to evaluate double pane IG. This was checked for accuracy against previously recorded data from experiments completed by Beason (1986a). The model developed by Beason (1986b), allows for the load sharing between the outer and inner plate of glass to be calculated based on a number of factors such as geometry, lateral load, glass thickness, gas space thickness (width of the spacer), and variations of both atmospheric pressure and gas space temperature. This model uses an iterative process that allows equilibrium to be reached while also satisfying gas space compatibility.

The allocation of loads acting on a double pane IG unit is shown in Fig. 4-3, with a uniform lateral load q_0 acting on the outer plate. This establishes that the outer plate net load q_1 can be summarized into:

$$q_1 = q_0 + P_a - P_{gs} \tag{1}$$

where P_a is the current atmospheric pressure and P_{gs} is the enclosed gas space pressure. Both of these values may be assumed to be the same for both the internal and external portions of the inside and outside plate. In a similar fashion, the inside plate can have its net load q_2 summarized into:

$$q_2 = P_{gs} - P_a \tag{2}$$

Combining these equations shows the relationship between the applied load and the net loads that act on each plate:

$$q_0 = q_1 + q_2 \tag{3}$$

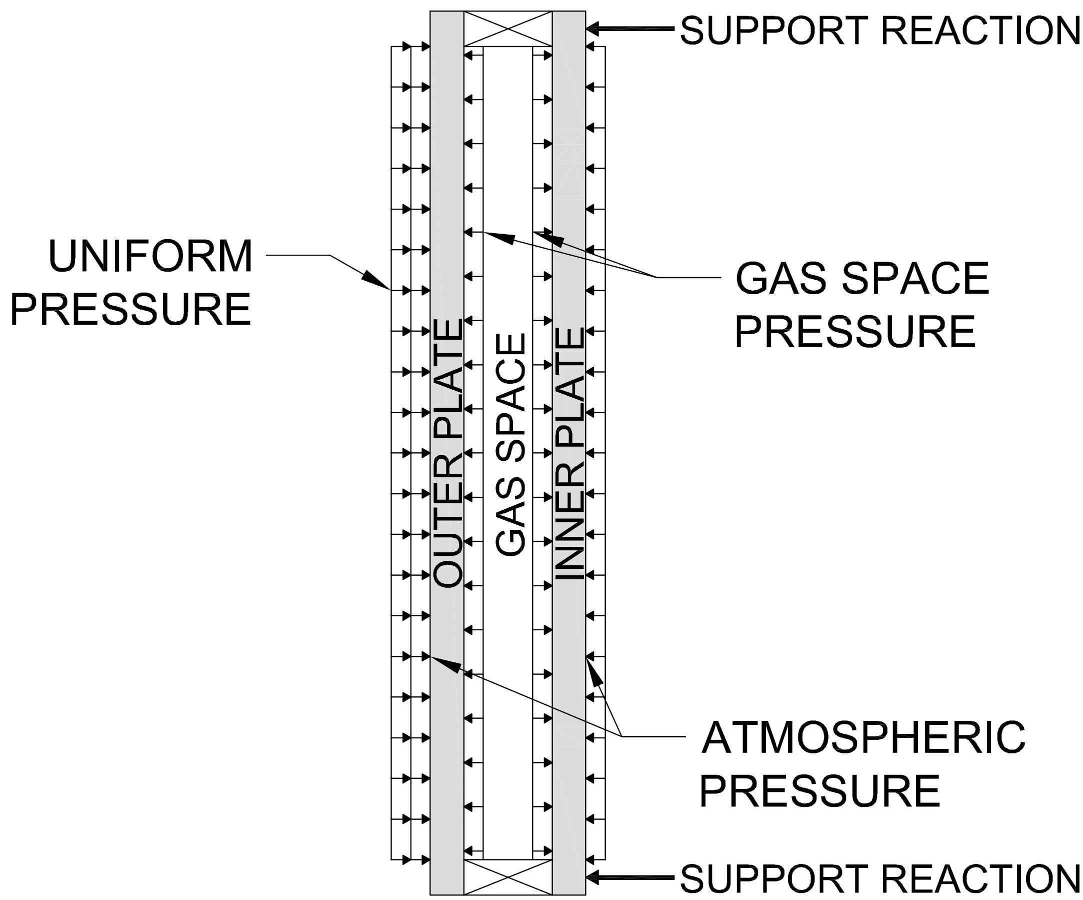

FIG. 4 - 3 Pressure distributions acting on a double pane insulating glass unit

GAS SPACE COMPATIBILITY

As the temperature in the gas space either heats up or cools down, initial loads begin to act on the double pane IG unit. When these act in conjunction with a uniform load, the load distribution may not be as it was predicted. As a result of the uniform pressure acting on the outer plate, the gas space pressure P_{gs} will vary. The gas contained in the gas space is assumed to act as an ideal gas, therefore the ideal gas law is used to find a constant C:

$$C = p_i * V_i / T_i \tag{4}$$

In equation (4) p_i, is defined as the initial atmospheric pressure, V_i, is the initial gas space volume of a sealed double pane IG unit, and T_i, is the initial gas space temperature measured in degrees Kelvin. To then find the current gas space pressure P_{gs}, insert the constant C into:

$$P_{gs} = C * T_{gs} / V_{gs} \tag{5}$$

where T_{gs}, is the current gas space temperature and V_{gs}, is the current gas space volume calculated as:

$$V_{gs} = V_i \pm V_1 \pm V_2 \tag{6}$$

where V_1, represents the displaced volume of the outer plate and V_2, represents the displaced volume of the inner plate. If the displaced volume of V_1 reduces the gas space, the sign is negative. If the displaced volume of V_1 increases the gas space, the sign is positive. If the displaced volume from V_2 decreases the volume, the sign is negative. If the displaced volume from V_2 increases the volume, the sign is positive. Note that the signs of V_1 and V_2 will be opposite of one another. Therefore, if the displaced volume from V_1 reduces the gas space and the sign is negative, the displaced volume from V_2 will increase the gas space and the sign will be positive. The signs need to be this way to balance out the pressure in the gas space.

To find the displaced volume of each plate, the nonlinear plate analysis developed by Vallabhan and Wang (1981) was used to determine the deflected shape of each plate. For the calculations in this paper, it was assumed that the edges of the plate were simply supported and free to slip in the plane of the plate. These edge conditions are an accepted way to model typical glass installations (Beason 1980). With the deflected shape determined by nonlinear plate analysis, the displaced volume is calculated by numerical integration across the surface of the plate. Fig. 4-4 displays a variety of aspect ratios and nondimensional loads. Interpolation can be done between the curves to cover all aspect ratios and loading conditions. The nondimensional lateral load $\hat{q}$ is calculated as:

$$\hat{q} = q * (a * b)^2 / (E * h^4) \tag{7}$$

where a is the long dimension and b is the short dimension of the rectangular double pane IG unit. E is the modulus of elasticity of the glass, q is the net uniform pressure applied to the plate, and h is the thickness of the plate being analyzed. The nondimensional displaced volume $\hat{V}$ is given as:

$$\hat{V} = V / (a * b * h) \tag{8}$$

where the only new term V is defined as the displaced volume in accordance with the nondimensional displaced volumes produced by nonlinear plate analysis (Vallabhan, 1981).

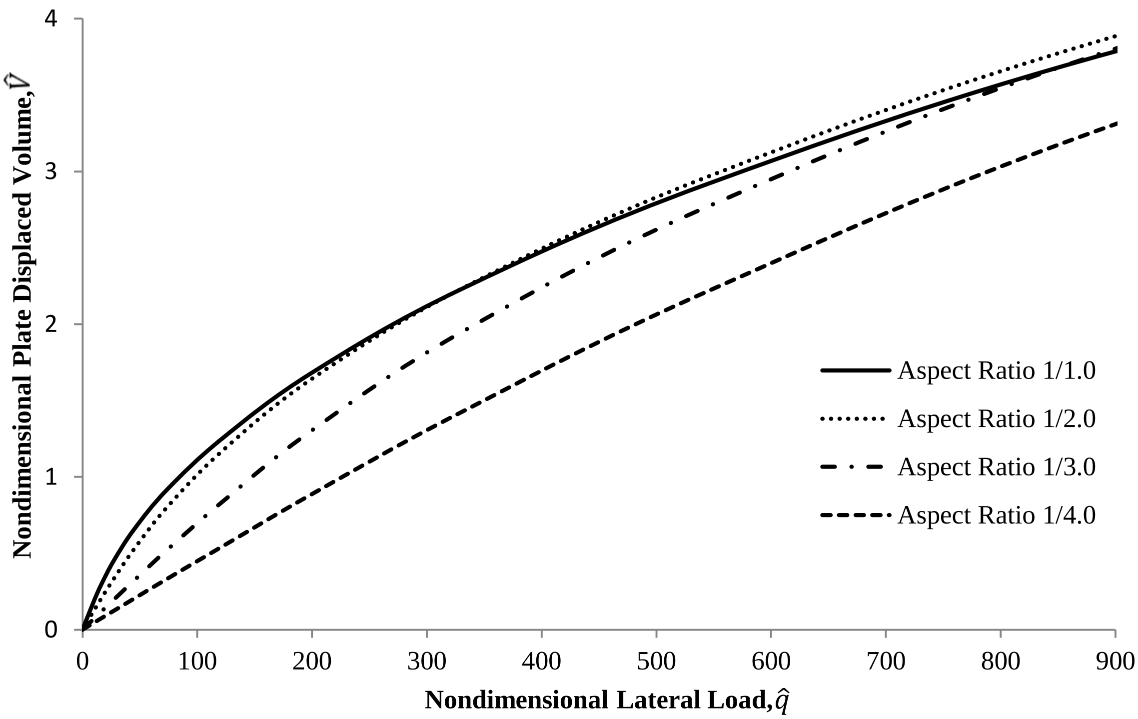

FIG. 4 - 4 Values of nondimensional plate displaced volume

ITERATIVE SOLUTION

In order to develop an iterative solution, a load distribution factor n is introduced to display the total net loads that act on the inner and outer plates. The expressions that display the loads acting on each plate of glass are:

$$q_1 = n * q_0 \tag{9}$$

and

$$q_2 = (1 - n) * q_0 \tag{10}$$

The variation in the atmospheric pressure, gas space temperature, and aspect ratio play a significant role in the size of the load distribution factor n. To find the load distribution factor, steps will be taken to iteratively converge on a solution. These begin with finding the net loads that act on the outer plate by combining equations (1) and (5) to get:

$$q_1 = q_0 + P_a - C * T_{gs}/V_{gs} \tag{11}$$

This equation can then be inserted into equation (9) and rearranged to find the load distribution factor n' for each iteration:

$$n' = 1 + P_a/q_0 - C * T_{gs}/(V_{gs} * q_0) \tag{12}$$

As a check on the accuracy of n' it is compared to n by creating an error factor $H(n)$:

$$H(n) = n - n' \tag{13}$$

Where an acceptable error of $1 * 10^{-12}$ is allowed so that the system would converge on an accurate solution. If n' is not within this acceptable level, n' replaces n in equation 9 and iterations are made using Matlab to find an acceptable solution.

DOUBLE PANE IG SPACER FLEXIBILITY

In the results produced by Beason (1986a), there was a discrepancy between what was produced in the double pane IG model and the test results. To address this discrepancy, an assumption was made that the spacer material was acting as a spring. This was tested using Hooke's Law, where the displacement of the spacer can be used to predict the force based on the stiffness of the spacer. When uniform pressure was applied to the outer plate, the spacer compressed slightly and transferred a portion of the load.

To investigate the application of Hooke's Law, an assumption was made to simplify the calculations. This assumption was that the plate will compress the spacer in a uniform manner. In essence, the plate would be rigid and equally distribute the load to all portions of the spacer.

The lateral load q_0 acting on the window was multiplied by the area of the window. This is represented by F:

$$F = q_0 * a * b \tag{14}$$

This was then divided by the perimeter of the rectangular double pane IG unit to convert the force to a theoretical number referred to as pounds per linear inch (PLI):

$$PLI = F/(2a + 2b) \tag{15}$$

Hooke's Law was then used to find the displacement, ΔS, that would occur from this force:

$$\Delta S = PLI/k \tag{16}$$

where k is the stiffness factor. Knowing the deflection in the spacer, the following equation multiplies the deflection by the area of the double pane IG unit to calculate the additional volume, V_s that would be reduced from the gas space:

$$V_s = \Delta S * a * b \tag{17}$$

This was then included in a new V_{gs} equation and reduced from the volume of the gas space:

$$V_{gs} = V_i \pm V_1 \pm V_2 - V_s \tag{18}$$

Once this new V_{gs} is established, it can be inserted into equation 11 and the procedure for finding the load distribution factor is the same as outlined above. For this procedure to work, an applicable stiffness factor needs to be established based off of spacer material.

Assuming that the spacer is made of Dow Corning 982 Silicone Insulating Glass Sealant, a Young's Modulus (E) of 350 psi was confirmed based upon multiple conversations with technical professionals at Dow Corning. This can then be used to find the deflection (Δ) of the spacer:

$$\Delta = PL/AE \tag{19}$$

Where P is the load applied to the spacer, and is equal to PLI. L is the width of the spacer, and A is the area of one linear inch of spacer. This equation can be combined with Hooke's Law (equation 16) and rearranged to equal:

$$k = AE/L \tag{20}$$

If the width of a spacer ranges from 1/8 in. – 1/2 in. a reasonable spacer stiffness (k) can be calculated as 50 lb/in. to 150 lb/in.

The effects of the spacer flexibility were examined by comparing results obtained from Beason (1986a). Spacer stiffness (k) values of 50 lb/in., 100 lb/in., and 150 lb/in. were applied to each available test. These values were compared against an infinite (rigid) spacer stiffness and the test data points. For these experiments a suction load was applied to the inner plate and there was no variation in atmospheric pressure or gas space temperature. The load distribution factor n that is reported in the figures below represents the load carried by the outer plate. This is represented in decimal form where 1.00 is the total load carried by both plates.

The results of these experiments show that the addition of spacer flexibility can more accurately evaluate load sharing between double pane IG units. Fig. 4-5 and Fig. 4-6 demonstrate that when realistic spacer flexibility values are introduced, the load factor (n) is more accurately presented. The parameters for these experiments are outlined in Table 4-1 and Table 4-2 respectively. However, the results obtained from these graphs do not completely match what is shown for every data point. Analyses of every experiment are presented in Appendix A.

While this experiment represents the introduction of spacer flexibility, more research needs to be done to fully evaluate how the behavior of the spacer actually affects load sharing in double pane IG units. These values may be used as the beginning of further testing to develop a complete understanding of load sharing combined with spacer flexibility.

TABLE 4 - 1 Experiment C132 test parameters

Outer Plate Thickness	0.103 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.19 in.
Long Dimension	20.59 in.
Gas Space Thickness	0.415 in.

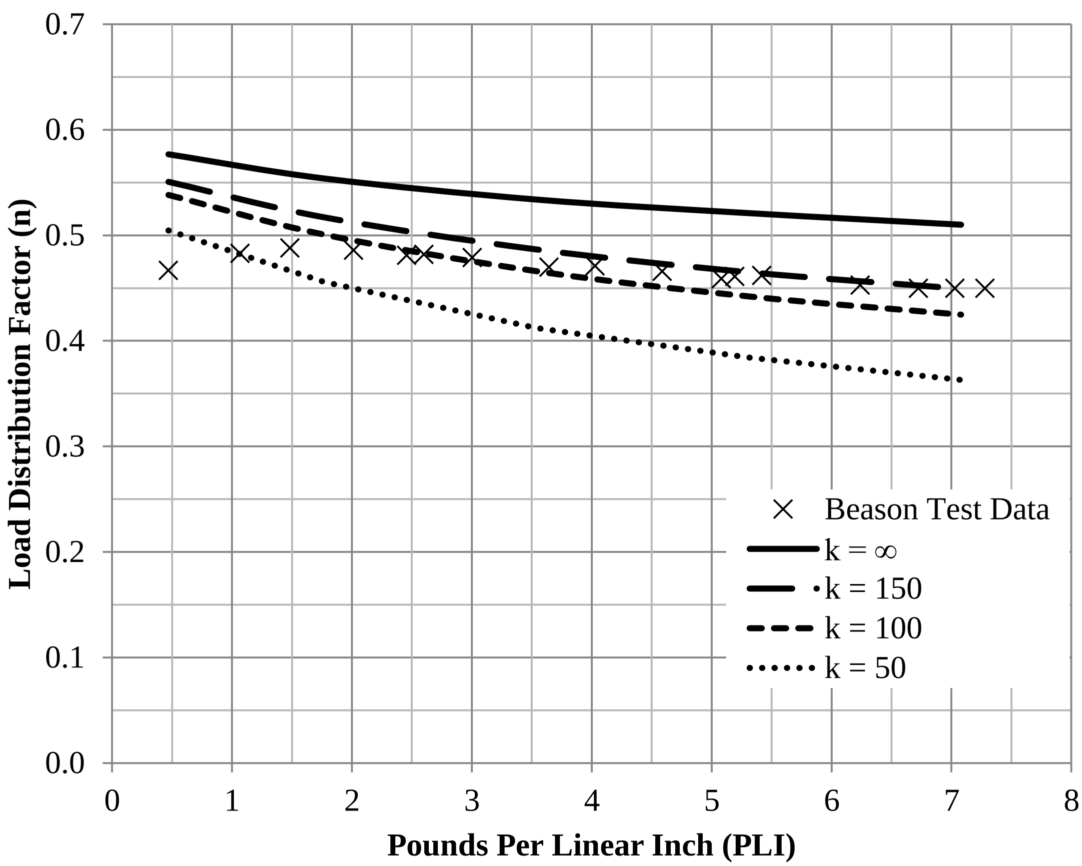

FIG. 4 - 5 Load distribution factor comparing infinite spacer stiffness and multiple stiffness factors

TABLE 4 - 2 Experiment C621 test parameters

Outer Plate Thickness	0.09 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	44.06 in.
Gas Space Thickness	0.415 in.

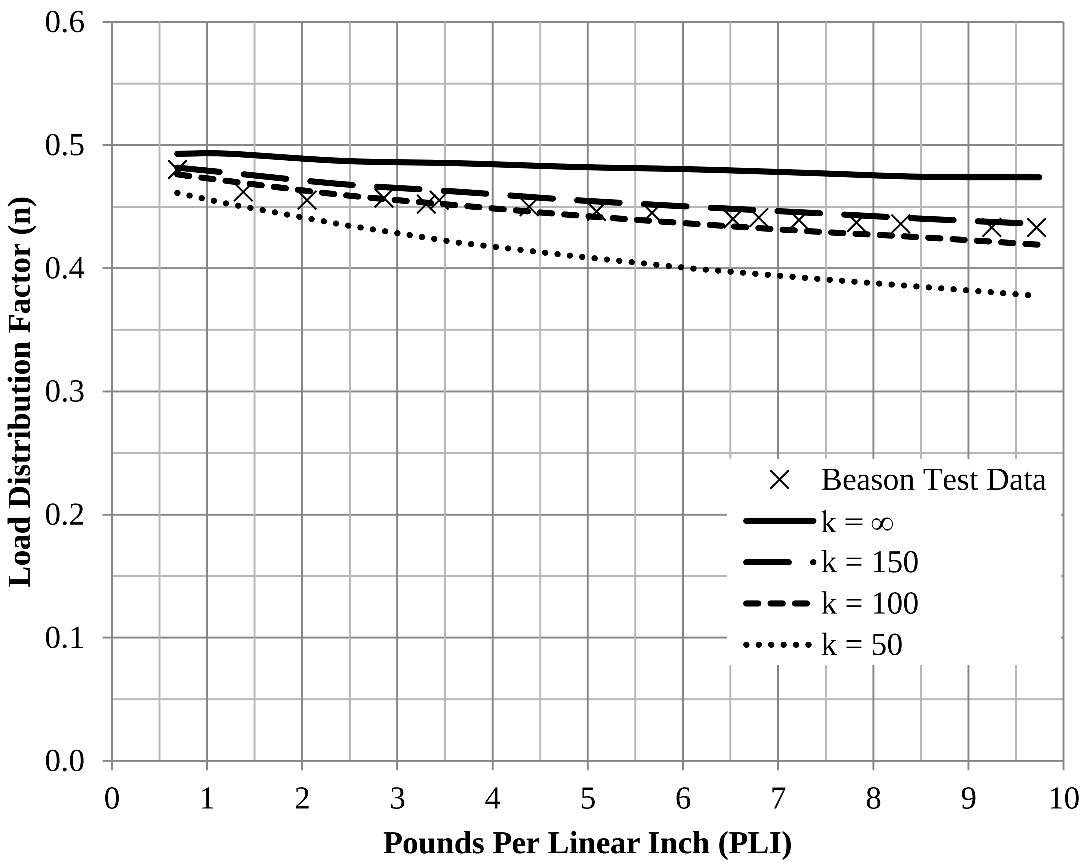

FIG. 4 - 6 Load distribution factor comparing infinite spacer stiffness and multiple stiffness factors

CHAPTER V

TRIPLE PANE INSULATING GLASS

In the effort to produce glass with greater insulating properties, manufacturers have introduced triple pane Insulating Glass (IG) units, consisting of an outer plate, inner plate, and middle plate. The middle plate divides the gas space into gas space 1 and gas space 2 as demonstrated in Fig. 5-1. Gas space 1 refers to the space between the outer plate and the middle plate, and gas space 2 refers to the space between the inner plate and the middle plate. In addition, there is a spacer that is placed around the perimeter of each plate of glass, creating a seal to prevent air and moisture from either entering or exiting the unit. Spacer 1 seals gas space 1, and spacer 2 seals gas space 2.

As with double pane IG units, a desiccant is placed inside the spacer to absorb any humidity that may have been trapped in the system during manufacturing. There can also be a capillary tube that will vent both gas spaces so that when the triple pane IG unit is installed, the pressure will have a chance to equalize. For research presented herein, it is assumed that both gas spaces are sealed so no gas can enter or exit from them.

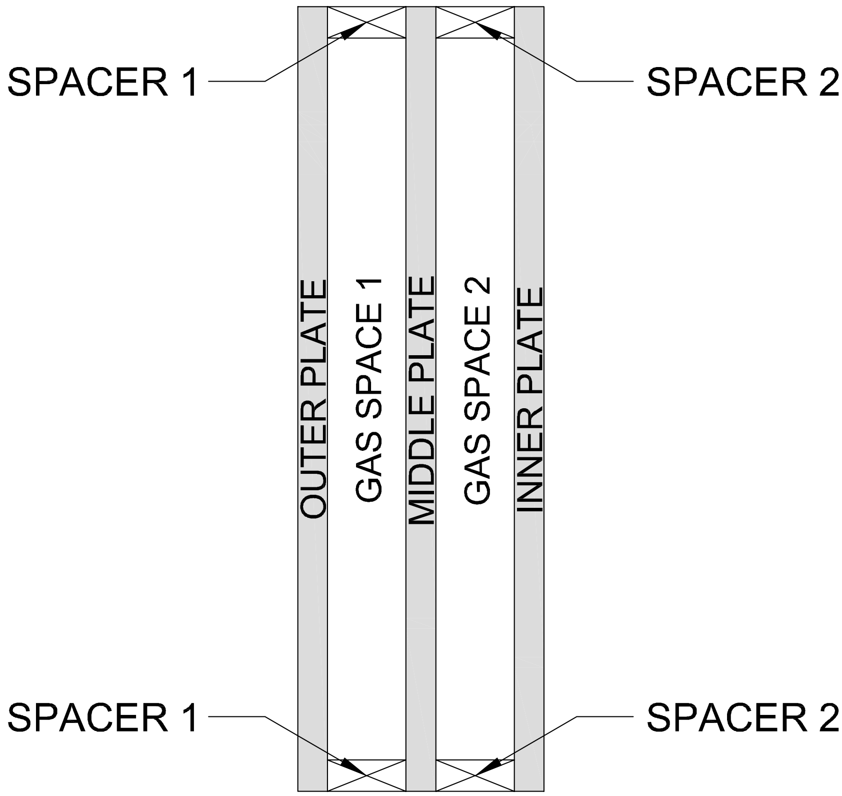

FIG. 5 - 1 Typical triple pane insulating glass cross section

When the triple pane IG unit is exposed to a uniform load of positive pressure, as demonstrated in Fig. 5-2, the outer plate will begin to deflect into the unit. This reduces the volume in gas space 1, resulting in an increase of pressure in gas space 1. To neutralize this pressure, the middle plate will begin to deflect into gas space 2 causing an increase of pressure in gas space 2. The increase of pressure in gas space 2 causes the inner plate to deflect neutralizing the pressure in the triple pane IG unit. These deflections mean that the load is shared between each plate of glass.

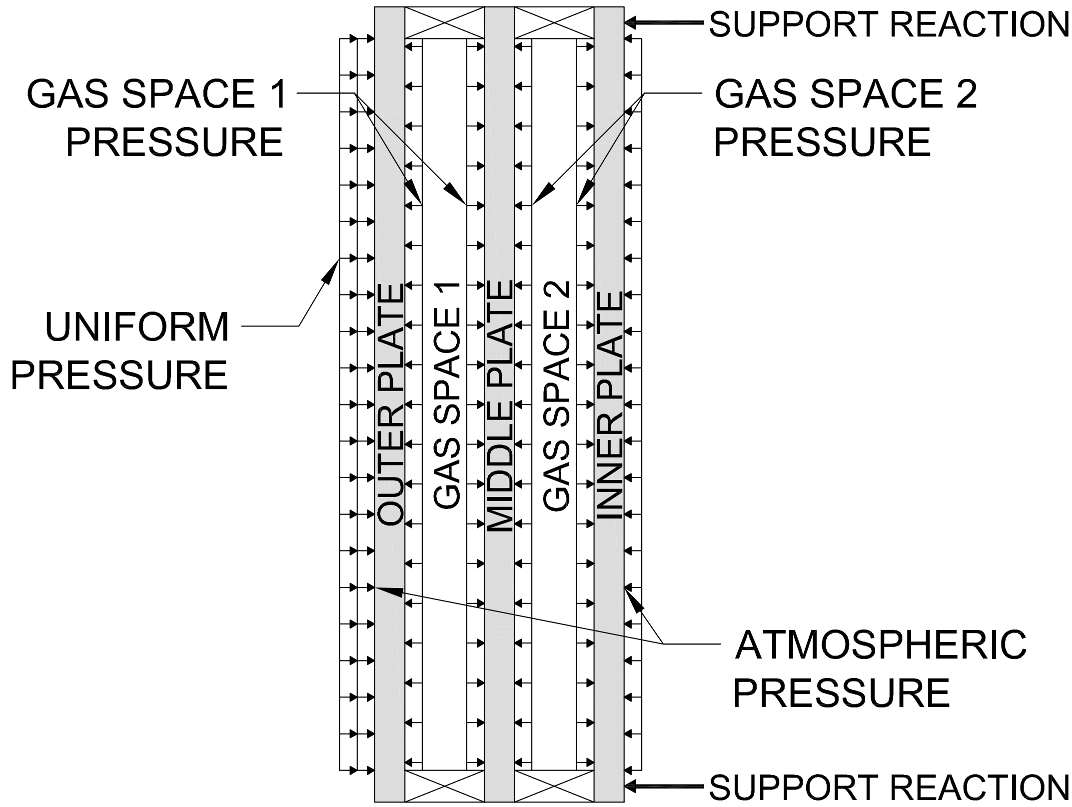

FIG. 5 - 2 Pressure distribution action on a triple pane insulating glass unit

TRIPLE PANE IG THEORETICAL LOAD SHARING ANALYSIS

The research model developed to evaluate triple pane IG load sharing was created using a similar theoretical evaluation as the double pane IG research model. This model allows theoretical load sharing between the outer, inner, and middle plate of glass to be calculated. The load sharing is dependent upon a variety of factors, including geometry, lateral load, thickness of each plate of glass, gas space thickness, variations in atmospheric pressure, and changes in gas space temperature. Similar to the model used for double pane IG, described in Chapter 4, this model allows equilibrium to be reached while satisfying gas space compatibility.

The distribution of the loads acting on a triple pane IG unit is demonstrated in Fig. 5-2, where there is a uniform positive pressure q_0 acting on the outer plate, the atmospheric pressure P_a acting on the outer and inner plates, the enclosed gas space 1 pressure P_{gs1} acting between the outer plate and middle plate, and the enclosed gas space 2 pressure P_{gs2} acting between the middle plate and the inner plate. Therefore, the net loads that act on the outer plate are:

$$q_1 = q_0 + P_a - P_{gs1} \tag{21}$$

The net loads acting on the middle plate are:

$$q_2 = P_{gs1} - P_{gs2} \tag{22}$$

The net loads acting on the inner plate are:

$$q_3 = P_{gs2} - P_a \tag{23}$$

Equations 21 – 23 can be combined and reduced to:

$$q_0 = q_1 + q_2 + q_3 \tag{24}$$

There are multiple factors that can affect the pressure change inside a triple pane IG unit. These factors include uniform pressure acting on the outer plate, variation in temperature gas space temperature, and change in atmospheric pressure outside the sealed triple pane IG unit.

The load sharing interaction in the unit begins in gas space 1. For this research, the gas trapped inside gas space 1 is considered to be an ideal gas. The ideal gas law is used to find the constant C_1. Note that a subscript of 1 refers to an interaction that is taking place inside gas space 1 unless otherwise stated:

$$C_1 = p_1 * V_1/T_1 \tag{25}$$

where p_1 is the gas space pressure, V_1 is the gas space volume, and T_1 is the absolute gas space 1 temperature in degrees Kelvin. To find the current pressure P_{gs1} of gas space 1 substitute C_1 into:

$$P_{gs1} = C_1 * T_{gs1}/V_{gs1} \tag{26}$$

with T_{gs1}, being the current gas space temperature and V_{gs1}, being the current gas space volume. V_{gs1}, is calculated by the deflections of the outer plate and the middle plate:

$$V_{gs1} = V_{i1} \pm V_1 \pm V_2 \tag{27}$$

where V_{i1}, is the initial volume in gas space 1, V_1, is the displaced volume due to the initial pressure in the outer plate, and V_2 is the displaced volume of the middle plate due to the increase of pressure in gas space 1. If the deflection of the plate increases the gas space, the sign is positive. Conversely, if the deflection of the plate decreases the gas space, the sign is negative. To find the displaced volume of an IG plate, nonlinear plate analysis established by Vallabhan and Wang (1981) is used by numerical integration across the surface of the plate. This will find the deflected shape of the plate using the assumption that the edges are simply supported and free to slip in the plane of the plate. Fig. 4-4 demonstrates various nondimensional displaced volumes with a range of nondimensional loads and aspect ratios. The nondimensional lateral load, $\hat{q}$ and the nondimensional displaced volume, $\widehat{V}$, are defined in equations 7 and 8 respectively.

The process of developing an iterative solution is more involved than with traditional double pane IG. It begins by writing the equilibrium equations for the outer plate, q_1:

$$q_1 = n_1 * q_0 \tag{28}$$

and the middle plate q_2:

$$q_2 = (1 - n_1) * q_0 \tag{29}$$

where n_1, is the load distribution factor between the outer plate and the middle plate. This factor is dependent upon the behavior of the plate, atmospheric pressure, and gas space temperature. The assumed value of n_1, distributes the load between the outer and middle plates.

The total load q_2, that acts on the middle plate will be distributed between the middle plate and the inner plate as if they were their own double pane IG unit within the triple pane IG system.

The area enclosed by the middle and inner plates is gas space 2, and requires a separate constant C_2 from the ideal gas law:

$$C_2 = p_2 * V_2/T_2 \tag{30}$$

where p_2, is the initial atmospheric pressure in gas space 2, V_2, is the initial volume in gas space 2, and T_2, is the initial temperature in gas space 2. This constant is then used to find the current pressure of gas space 2 P_{gs2}:

$$P_{gs2} = C_2 * T_{gs2}/V_{gs2} \tag{31}$$

where T_{gs2}, is the current temperature of gas space 2 and V_{gs2}, is the current volume of gas space 2 calculated as:

$$V_{gs2} = V_{i2} \pm V_2 \pm V_3 \tag{32}$$

where V_{i2} is the initial volume of gas space 2, V_2 is the displaced volume due to the increase in pressure on the middle plate, and V_3 is the displaced volume due to the increase of pressure in gas space 2 on the outer plate. If the deflection of the plate increases the volume of the gas space, the sign is positive. While if the deflection of the plate decreases the volume of the gas space, the sign is negative. Similar to gas space 1, nonlinear plate analysis is used to find the nondimensional displaced volumes of the middle plate and inner plate using the logic provided by equations 7 and 8.

A simultaneous iterative solution is satisfied for the middle plate and the inner plate resolving the load placed on the middle plate in equation 29 into:

$$q_{2C} = n_2 * q_2 \tag{33}$$

where n_2 is the load distribution factor between the middle plate and the inner plate and q_{2C} is the assumed load carried by the middle plate. This is dependent upon both n_1 and n_2. The n_2 factor is also dependent upon the behavior of the plate, atmospheric pressure, and gas space temperature. The load placed on the inner plate is simply:

$$q_3 = q_0 - q_1 - q_2 \tag{34}$$

The next step is to combine equations 21 and 26 to modify the expression for the load acting on the outer plate:

$$q_1 = q_0 + p_a - C_1 * T_{gs1}/V_{gs1} \tag{35}$$

This equation can be combined with equation 28 and rearranged to create a calculation for a revised load distribution factor n_1':

$$n_1' = 1 + P_a/q_0 - C_1 * T_{gs1}/(V_{gs1} * q_0) \tag{36}$$

that is based on an original estimate n_1 used to calculate the volume in gas space 1 as well as the current atmospheric pressure and temperature of gas space 1. In similar fashion, equations 22 and 31 can be combined to show an expression for the net loads acting on the middle plate:

$$q_2 = C_1 * T_{gs1}/V_{gs1} - C_2 * T_{gs2}/V_{gs2} \tag{37}$$

This equation can be combined with equation 33 and rearranged to create a calculation for a revised load distribution factor n_2':

$$n_2' = C_1 * T_{gs1}/(V_{gs1} * (q_0 - q_1)) - C_2 * T_{gs2}/(V_{gs2} * (q_0 - q_1)) \quad (38)$$

this is based on an original estimate of n_2 used to calculate the volume in gas space 2 as well as the current atmospheric pressure and temperature of gas space 2. Equation 38 is solved simultaneously with equation 36 so that both load distribution factors can be used to solve the load acting on all three plates.

As a check on the accuracy of n_1' and n_2' they are compared to n_1 and n_2 respectively by creating error functions $H(n_1)$ and $H(n_2)$:

$$H(n_1) = n_1 - n_1' \quad (39)$$

$$H(n_2) = n_2 - n_2' \quad (40)$$

Where an acceptable error of $1 * 10^{-12}$ is allowed so that the system would converge on an accurate solution. If n_1' is not within the acceptable level n_1' replaces n_1 in equation 28 and iterations are made using Matlab to find an acceptable solution. Likewise if n_2' is not within the acceptable level n_2' replaces n_2 in equation 33 and iterations are made using Matlab to find an acceptable solution.

TRIPLE PANE IG SPACER FLEXIBILITY

To evaluate spacer flexibility in triple pane IG units, the same approach used to evaluate spacer flexibility in double pane IG units was applied to the model. This approach used Hook's Law to transfer loads through the unit. To simplify calculations, an assumption was made that the plate would compress the spacer in a uniform manner. In essence, the plate would be rigid and equally distribute the load to all portions of the spacer.

To evaluate spacer flexibility in spacer 1, the lateral load q_1 acting on the outer plate was multiplied by the area of the window. This is represented by F_1:

$$F_1 = q_1 * a * b \tag{41}$$

This was then divided by the perimeter of the rectangular triple pane IG unit to convert the force to a theoretical number referred to as pounds per linear inch 1 (PLI1):

$$\mathrm{PLI1} = F_1/(2a + 2b) \tag{42}$$

Hooke's Law was then used to find the displacement ΔS1, that would occur from this force:

$$\Delta \mathrm{S1} = \mathrm{PLI1}/k \tag{43}$$

where k, is the stiffness factor in the spacer with units of lb/in. Because of this deflection, the volume in gas space 1 will be reduced:

$$V_{s1} = \Delta \mathrm{S1} * a * b \tag{44}$$

where V_{s1}, is the volume from the deflection of the spacer in gas space 1. This volume was then reduced from the total volume in gas space 1:

$$V_{gs1} = V_{i1} \pm V_1 \pm V_2 - V_{s1} \tag{45}$$

With a new value for the volume of gas space 1, the procedure for finding the load distribution factor n_1, is the same as outlined starting in equation 28.

To evaluate spacer flexibility in spacer 2 the lateral load q_{2C} acting on the middle plate was multiplied by the area of the window. This is represented by F_2:

$$F_2 = q_{2C} * a * b \tag{46}$$

This was then divided by the perimeter of the rectangular triple pane IG unit to convert the force to a theoretical number referred to as pounds per linear inch 2 (PLI2):

$$PLI2 = F_2/(2a + 2b) \tag{47}$$

Hooke's Law was then used to find the displacement ΔS2, that would occur from this force:

$$\Delta S2 = PLI2/k \tag{48}$$

Note that the stiffness factor k used here is the same as what was used for spacer 1. This is because the material in both spacers is the same. The deflection is then broken into a volume by multiplying by the area of the unit:

$$V_{s2} = \Delta S2 * a * b \tag{49}$$

where V_{s2}, is the reduced volume from the spacer stiffness in gas space 2. It is then taken out of the total volume of gas space 2:

$$V_{gs2} = V_{i2} \pm V_2 \pm V_3 - V_{s2} \tag{50}$$

Once the new volume of gas space 2 is calculated, the load distribution factor n_2, is calculated using the same technique described beginning in equation 33.

TRIPLE PANE IG RESULTS

Results for triple pane IG were conducted using three standard window sizes from the American Architectural Manufacturers Association (AAMA). The selected hung window sizes evaluated in this research are presented in Table 5-1. Note that the first two test sizes are for vertically sliding hung windows. This means that the long dimension will be cut in half because the unit will be divided into two plates of glass.

TABLE 5 - 1 AAMA typical sizes for vertically hung windows

Window Type	Total Dimension	Short Test Dimension	Long Test Dimension	Applied Lateral Load
R-RG15-H	40"x63"	*31.5"	40"	15 psf
CW-PG30-H	56"x91"	*45.5"	56"	30 psf
AW -PG40-H	60"x99"	60"	99"	40 psf

*Vertically sliding hung windows

EFFECT OF SPACER FLEXIBILITY

When the double pane IG units were evaluated a spacer stiffness (k) value of 50 lb/in. to 150 lb/in. was used. These tests more accurately predicted the load sharing relationship between double pane IG units. For triple pane IG units a spacer stiffness (k) value of 100 lb/in. will be analyzed in the three test windows described above. These results are presented in Table 5-2.

TABLE 5 - 2 Triple pane insulating glass results from spacer flexibility

Window Type	Outer Plate Load			Middle Plate Load			Inner Plate Load		
	k = ∞	k = 100 lb/in.	% Diff	k = ∞	k = 100 lb/in.	% Diff	k = ∞	k = 100 lb/in.	% Diff
R-RG15-H	5.17	4.91	4.93%	4.97	4.97	0.00%	4.87	5.12	5.25%
CW-PG30-H	10.24	9.72	5.06%	9.95	9.95	0.00%	9.81	10.33	5.32%
AW -PG40-H	13.60	12.74	6.30%	13.28	13.27	0.00%	13.12	13.99	6.62%

This analysis shows that when spacer flexibility is applied to the unit a portion of the load is transferred from the outer plate to the inner plate. This causes a slightly higher percentage of the load to be carried by the inner plate than the outer plate. There is a shift that is seen from performing this analysis using spacer flexibility, but the shift in load does not seem large enough to affect the load sharing relationship of the triple pane IG unit. Therefore the remaining analysis will be completed using a rigid spacer.

ATMOSPHERIC PRESSURE DROP

The average barometric pressure at sea level is 1013 millibars which is equivalent to 14.7 psi. A falling barometric pressure is the indication that a storm is approaching. With some storms this can be a rapid substantial decrease. In hurricanes there is also a barometric pressure decrease near the storms center. Hurricane Wilma in 2005 marked the lowest pressure in a hurricane which was recorded at 882 millibars. This is equivalent to an almost 2 psi drop from the average barometric pressure.

A drop in barometric pressure will cause the outer plate and inner plate of a triple pane IG unit to bow outward as seen in Fig. 5-3. Because the pressure inside gas space 1 and gas space 2 is greater than the atmospheric pressure, the outer plate and inner plate will receive some initial load. This initial load is not significant enough to cause problems in the unit. However, when this is combined with a lateral wind pressure on the outer plate, the load carried by the inner plate will be greater than the initial design.

The analysis in this section will evaluate the effect that an atmospheric pressure drop has on a triple pane IG unit and how it could affect the way a unit is sized. Using the three units outlined in Table 5-1 the plates were sized using the specified design lateral pressure in a balanced unit. The unit will be analyzed with this size. It can then be seen whether or not the atmospheric pressure drop will cause any of the plates to become overloaded.

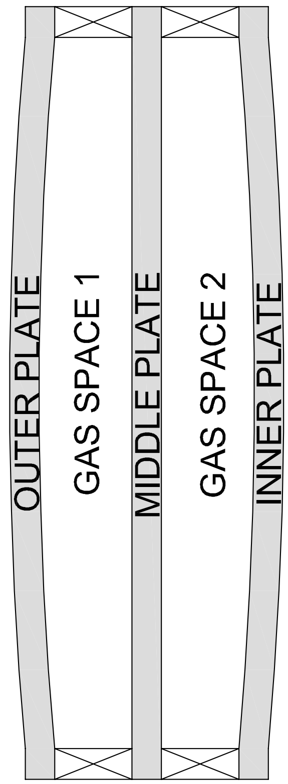

FIG. 5 - 3 Triple pane insulating glass unit with low atmospheric pressure and high gas space temperature

Using the glass thickness design charts (ASTM E1300) the R-RG15-H unit can be sized with 3/32" glass. For this aspect ratio and glass thickness each plate of glass can carry over 31 psf. The unit is tested for a maximum pressure of 15 psf, from Table 5-2 the design load on the outer plate is 5.17 psf. This means that even though the smallest glass thickness was selected, the unit is significantly over designed.

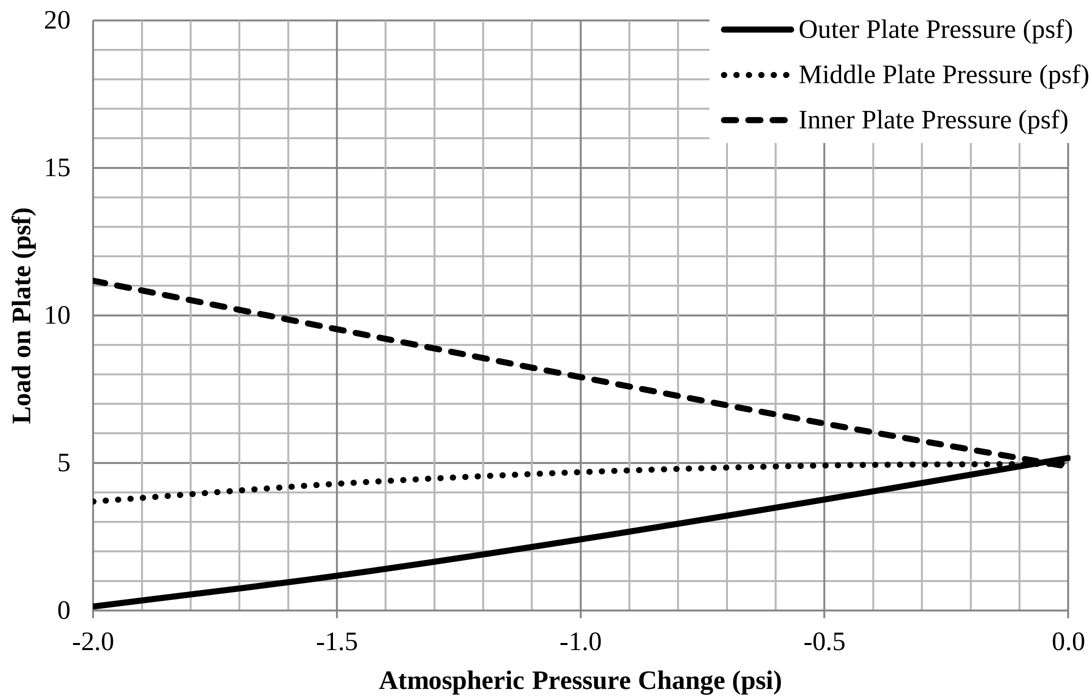

FIG. 5 - 4 Variation due to constant load on R-RG15-H unit as atmospheric pressure is dropped 2 psi

In Fig. 5-4 it is apparent that as the atmospheric pressure drops a high percentage of the load is transferred to the inner plate. However, since this plate is significantly over designed, the pressure drop does not require the plate to be resized.

From the glass thickness design charts (ASTM E1300) the CW-PG30-H unit can also be sized with 3/32" glass. For this aspect ratio and glass thickness each plate of glass can carry about 17 psf. The unit is tested for a maximum pressure of 30 psf, from Table 5-2 the design load on the outer plate is 10.24 psf.

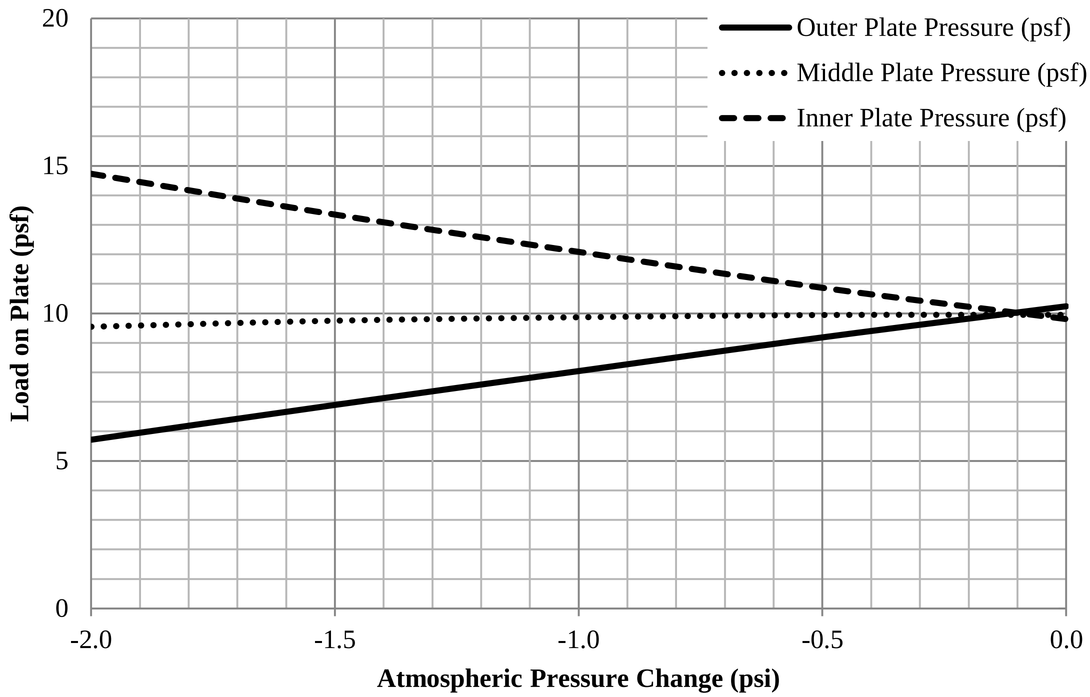

FIG. 5 - 5 Variation due to constant load on CW-PG30-H unit as atmospheric pressure is dropped 2 psi

From Fig. 5-5 it is apparent that as the atmospheric pressure is reduced, the load carried by the inner plate is increased to roughly 15 psf. This increase is high but similar to the R-RG15-H unit, the plate was significantly overdesigned and the increase does not cause the plate to be resized.

For the AW-PG40-H unit each plate can be sized as a 5/32" from the glass thickness design charts (ASTM E1300). For this aspect ratio and glass thickness each plate of glass can carry slightly over 17 psf. The unit is tested for a maximum pressure of 40 psf, from Table 5-2 the design load on the outer plate is 13.60 psf.

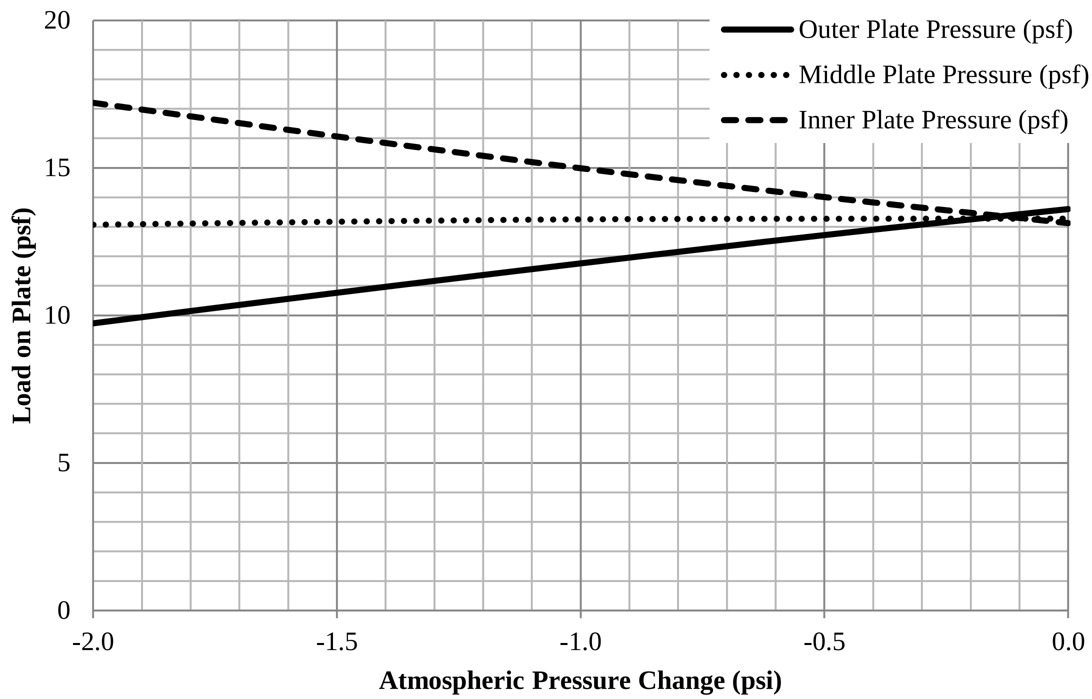

FIG. 5 - 6 Variation due to constant load on AW-PG40-H unit as atmospheric pressure is dropped 2 psi

From Fig. 5-6 it is apparent that the pressure drop causes the load carried by the inner plate to increase to just over 17 psf. Because each plate was originally designed for a load of slightly over 17 psf, this places the unit on the border as to whether or not it would need to be resized.

From these three tests it is apparent that atmospheric pressure variations have a significant impact on the load sharing relationship in a triple pane IG unit.

GAS SPACE TEMPERATURE VARIATIONS

When temperature in the gas space either heats up or cools down initial loading begins to take place on the outer plate and inner plate of the triple pane IG unit. When the temperature increases the outer plate and inner plate begin to bow out as seen in Fig. 5-3. When the temperature decreases the outer plate and inner plate begin to bow in as seen in Fig. 5-7. These effects cause the outer plate and the inner plate to become preloaded. This initial load combined with a uniform pressure is what will be discussed in this section. The three units outlined in Table 5-1 will be used for these tests. Gas space temperature will be evaluated from 0 degrees F to 120 degrees F with initial gas space temperature set at 70 degrees F.

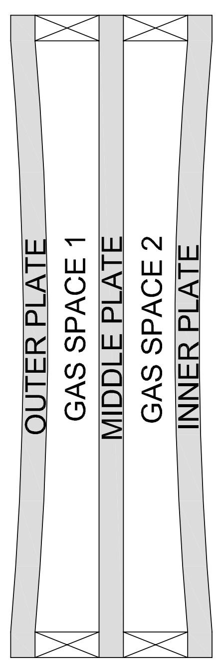

FIG. 5 - 7 Triple pane insulating glass unit with low gas space temperature

As previously discussed in the atmospheric pressure section the glass plate design thickness for an R-RG15-H unit is 3/32" (ASTM E1300). For this aspect ratio and glass thickness each plate of glass can carry over 31 psf. The unit is tested for a total pressure of 15 psf and the total load carried by the outer plate is 5.17 psf as shown in Table 5-2.

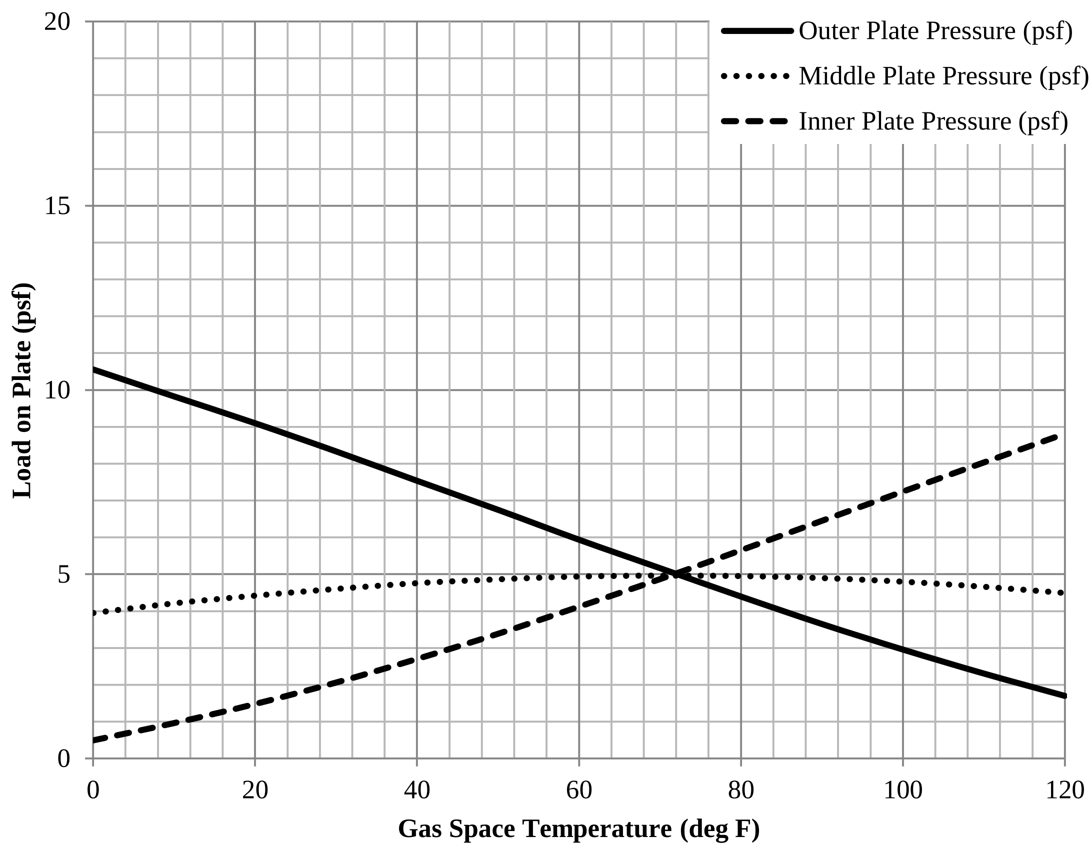

FIG. 5 - 8 Variation due to constant load on R-RG15-H unit as gas space temperature is varied

Fig. 5-8 shows that as the gas space temperature drops to 0 degrees F, the load carried by the outer plate is around 10.5 psf. This is twice the load carried by this plate which is a significant increase. However, because the plate is significantly overdesigned this additional loading does not require the plate to be redesigned.

For the CW-PG30-H unit the required plate thickness is 3/32" (ASTM E1300). For the aspect ratio and glass thickness each plate of glass can carry about 17 psf. The unit is tested for a total pressure of 30 psf and from Table 5-2 the outer plate carries 10.24 psf.

In Fig. 5-9 it is obvious that temperature variation causes the load carried by the outer plate to increase as the temperature drops. This total load carried by the outer plate at the low extreme is roughly 14.5 psf. This is an increase in loading, but because this plate was overdesigned from the beginning, this plate does not need to be redesigned.

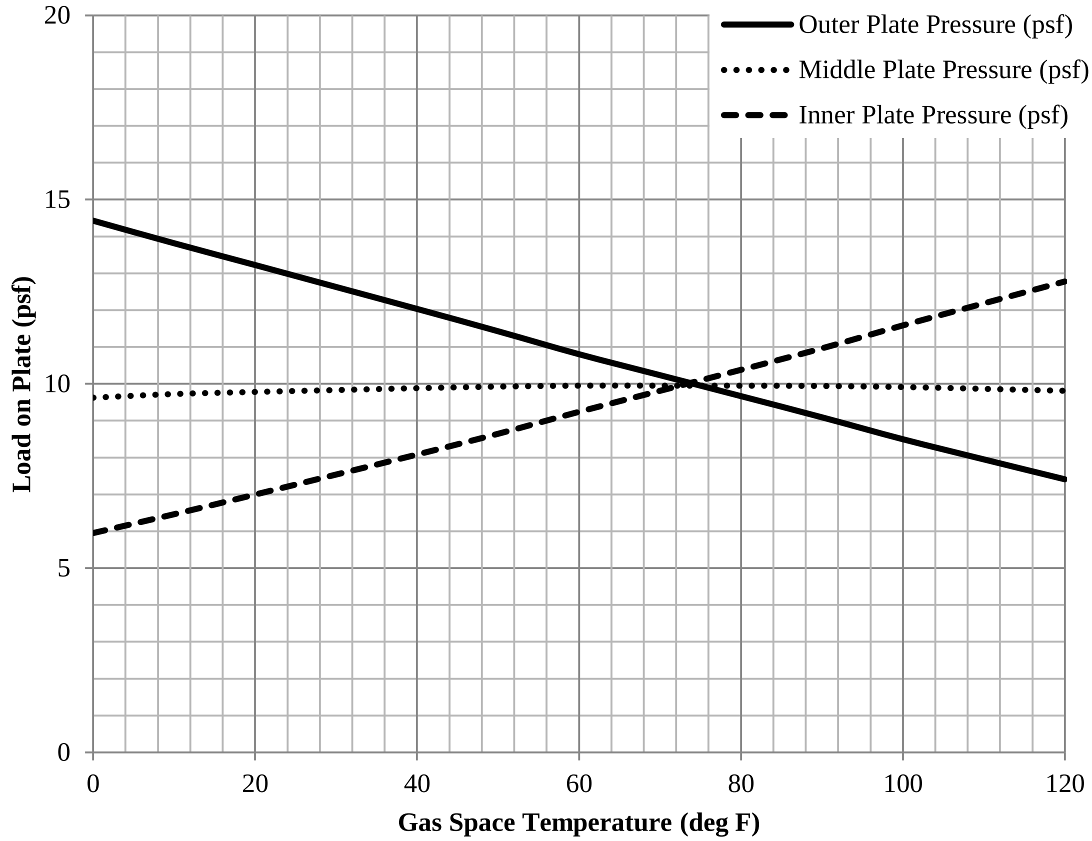

FIG. 5 - 9 Variation due to constant load on CW-PG30-H unit as gas space temperature is varied

In the AW-PG40-H unit each plate is sized as a 5/32" from the glass thickness design charts (ASTM E1300). For this aspect ratio and glass thickness each plate of glass can carry slightly over 17 psf. The unit is tested for a maximum pressure of 40 psf, from Table 5-2 the design load on the outer plate is 13.60 psf.

Fig. 5-10 shows that as the gas space temperature is reduced the load carried by the outer plate in increased to 17 psf. This is slightly below what this plate was designed for so the glass thickness is appropriate.

The results presented in this section show that temperature fluctuations do cause variations in the loading of triple pane IG units.

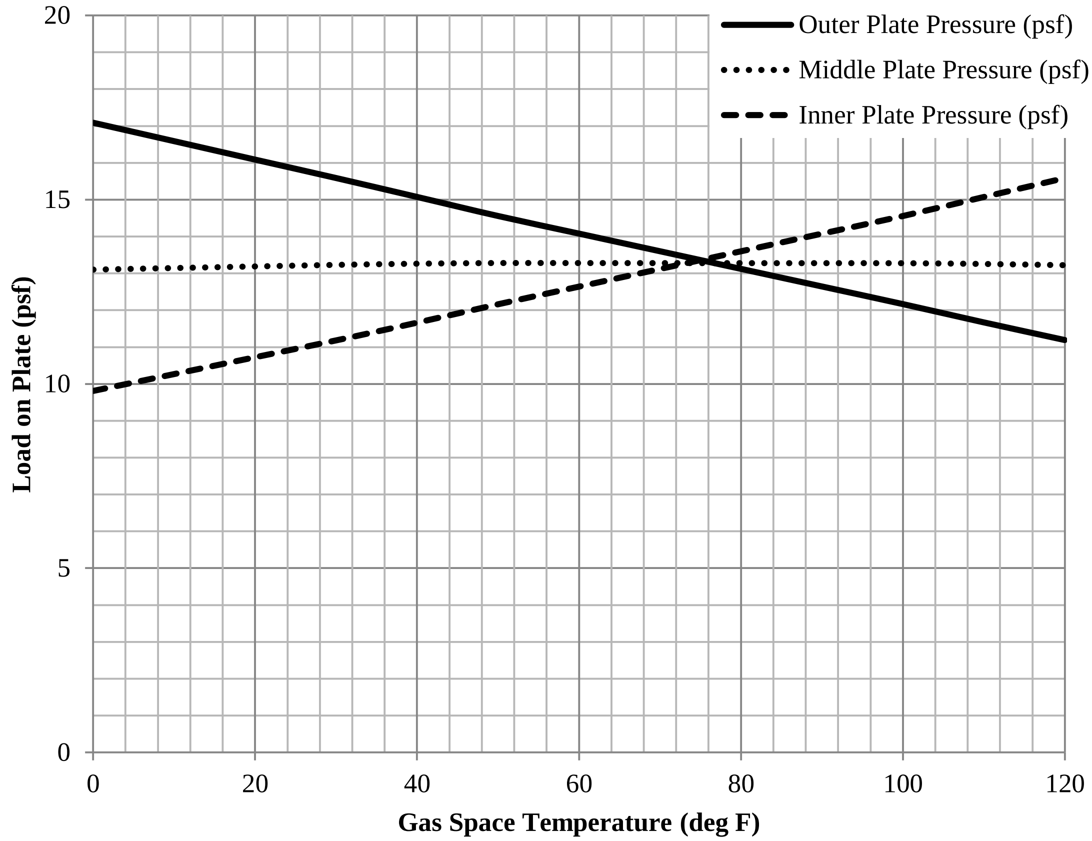

FIG. 5 - 10 Variation due to constant load on AW-PG40-H nit as gas space temperature is varied

TRIPLE PANE IG LOAD SHARING FREE BODY DIAGRAM CHECK

To ensure that the Matlab model was producing accurate results, calculations were completed using a free body diagram approach. For this calculation, the load carried by each plate was estimated and then each plate was analyzed with this load and checked and the results were compared against what was originally predicted. Hand iterations were completed to converge on a solution that verified what was being produced in the triple pane IG load sharing model were correct.

COMPARISON WITH PREVIOUS RESEARCH

In previous research published in Glass Performance Days, Norville (2011) developed a solution that used nonlinear analysis along with the nondimensional displaced volume and the nondimensional load to determine the load sharing between the three plates of glass. This is a similar approach to what was used in this paper to develop a solution.

The three examples from this work are outlined in the tables below. Since the paper was written in SI units, all dimensions and loads were converted to English units. These conversions are displayed in Table 5-3 to give a complete description of what was entered into the research model. In the experiment conducted by Norville, it was assumed that the gas spaces were at ambient temperatures and pressures.

The results from example 1 are displayed in Table 5-4. In this standard rectangular unit with equal plate thickness and equal gas space thickness, the results from the research model and the experiments that Norville ran produced identical experimental results to the research model. The section comparing the results to the ASTM values was also taken from Norville (2011).

Results from the second example, which are displayed in Table 5-5, do not match what was reported by Norville (2011). The ASTM loads presented in this section are also what was reported by Norville (2011). There is a discrepancy that lies in the load carried by the outer plate. General load checks for this unit are displayed at the bottom of the table and the total load carried by the three plates does not match the initial load entered into the unit.

Table 5-6 shows the results from example 3, and demonstrates the load sharing between a smaller rectangular triple pane IG unit with less flexible plates. Here the research model produced a much higher result for the load carried by the outer plate. General load checks for this units are displayed at the bottom of the table and the total load carried by the three plates does not match the initial load entered into the unit.

The results from example 2 and 3 do not match what was produced by Norville (2011).

TABLE 5 - 3 Dimensions of Norville (2011) examples

Example	kPa	psf		mm	in
1	3.2	66.83	Short Dimension	965	38
			Long Dimension	1930	76
			Outer Plate Thickness	3	0.12
			Middle Plate Thickness	3	0.12
			Inner Plate Thickness	3	0.12
			Gas Space 1 Thickness	9	0.35
			Gas Space 2 Thickness	9	0.35
2	3.2	66.83	Short Dimension	965	38
			Long Dimension	1930	76
			Outer Plate Thickness	6	0.24
			Middle Plate Thickness	4	0.16
			Inner Plate Thickness	3	0.12
			Gas Space 1 Thickness	12	0.47
			Gas Space 2 Thickness	12	0.47
3	11.1	231.83	Short Dimension	508	20
			Long Dimension	762	30
			Outer Plate Thickness	3	0.12
			Middle Plate Thickness	3	0.12
			Inner Plate Thickness	3	0.12
			Gas Space 1 Thickness	6	0.24
			Gas Space 2 Thickness	6	0.24

TABLE 5 - 4. Results from Example 1 of Norville Experiments

Example 1						
	Research Model			Norville		ASTM
	psf	kPa	% Diff Norville	kPa	% Diff ASTM	kPa
Outer Plate	22.93	1.10	0.00%	1.10	2.73%	1.07
Middle Plate	22.28	1.06	0.00%	1.06	0.94%	1.07
Inner Plate	21.75	1.04	0.00%	1.04	2.88%	1.07
Load Check	66.83	3.20		3.20		3.21

TABLE 5 - 5. Results from Example 2 of Norville Experiments

Example 2						
	Research Model			Norville		ASTM
	psf	kPa	% Diff Norville	kPa	% Diff ASTM	kPa
Outer Plate	45.02	2.16	10.65%	1.93	6.02%	2.03
Middle Plate	14.75	0.71	3.66%	0.684	9.86%	0.640
Inner Plate	7.06	0.34	4.71%	0.356	14.71%	0.294
Load Check	66.83	3.21		2.97		2.96

TABLE 5 - 6. Results from Example 3 of Norville Experiments

Example 3						
	Research Model			Norville		ASTM
	psf	kPa	% Diff Norville	kPa	% Diff ASTM	kPa
Outer Plate	89.41	4.28	47.44%	2.23	13.57%	3.70
Middle Plate	74.62	3.57	0.21%	3.58	3.57%	3.70
Inner Plate	67.81	3.25	0.72%	3.27	13.97%	3.70
Load Check	231.84	11.10		9.08		11.10

CHAPTER VI

CONCLUSIONS

The purpose of this thesis was to develop an understanding of the spacer flexibility in an insulating glass (IG) unit, and to develop a load sharing relationship between triple pane IG units when a uniform pressure was applied to the outer plate of the unit. The experiments were conducted using computer software that was able to model the load sharing relationship between double pane IG and triple pane IG units, and determine the ratio of the load that was carried between each plate of glass in the respective unit.

The research conducted shows that a portion of the load is transferred to the inner plate when spacer flexibility is applied. It is also possible to predict the behavior in triple pane IG units when atmospheric pressure is reduced and when the gas space temperature is adjusted.

The major conclusions that can be drawn from this research are as follows:

1. Spacer flexibility can act like a spring and transfer load from the outer plate to the inner plate.
2. The research demonstrates that when the atmospheric pressure drops, a significant amount of load is transferred to the inner plate as was originally predicted.

3. The research demonstrates that when the gas space temperature changes, the loads carried by the inner plate and the outer plate vary significantly from what was originally predicted.

The questions answered in this research create an understanding into the load sharing relationship within triple pane IG units. Further research should be conducted doing physical tests to compare against these results.

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APPENDIX A

SPACER FLEXIBILITY ANALYSIS OF BEASON TEST RESULTS

TABLE A - 1 Experiment C111 test parameters

Outer Plate Thickness	0.09 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.19 in.
Long Dimension	20.59 in.
Gas Space Thickness	0.415 in.

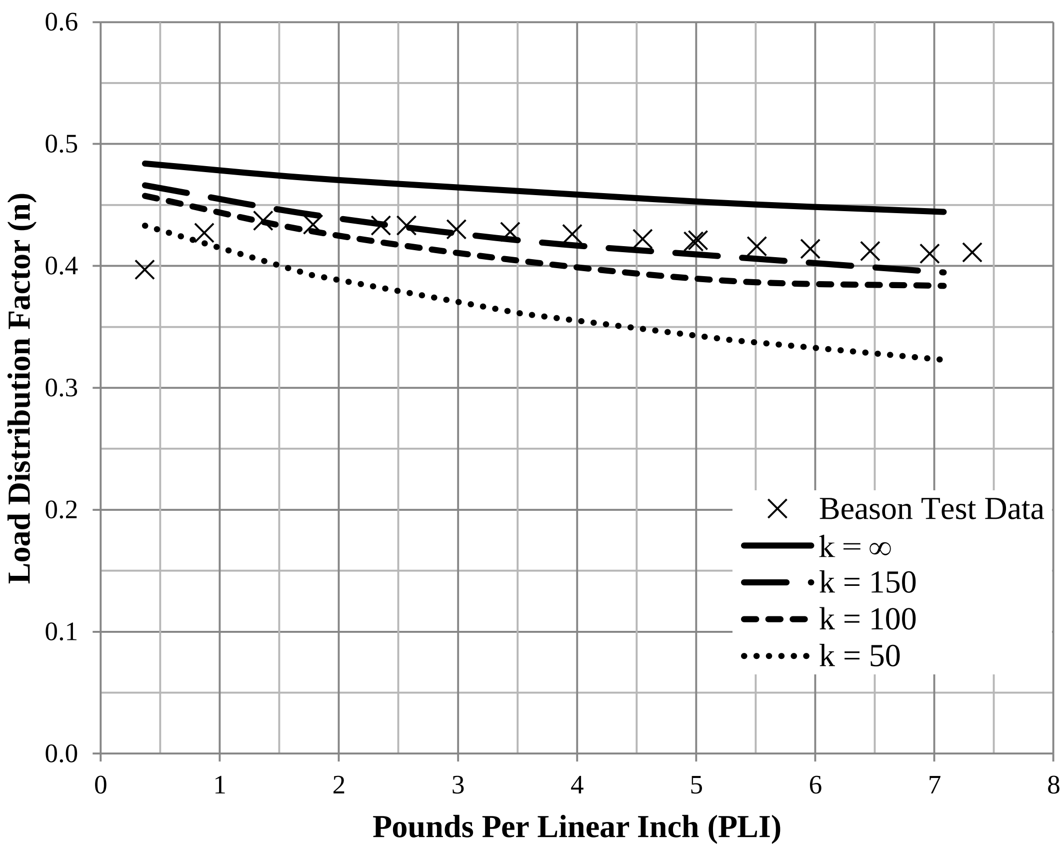

FIG. A - 1 Experiment C111 test result comparison with spacer flexibility

TABLE A - 2 Experiment C121 test parameters

Outer Plate Thickness	0.095 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.19 in.
Long Dimension	20.59 in.
Gas Space Thickness	0.415 in.

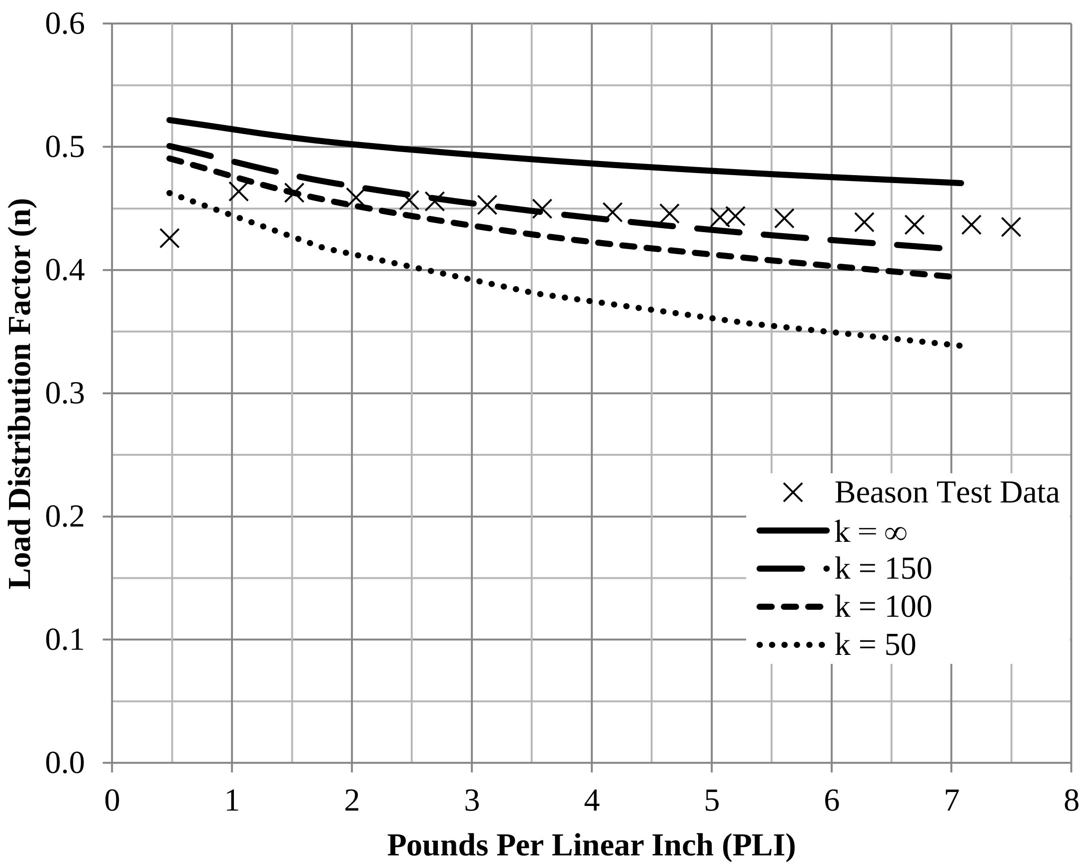

FIG. A - 2 Experiment C121 test result comparison with spacer flexibility

TABLE A - 3 Experiment C122 test parameters

Outer Plate Thickness	0.095 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.19 in.
Long Dimension	20.59 in.
Gas Space Thickness	0.415 in.

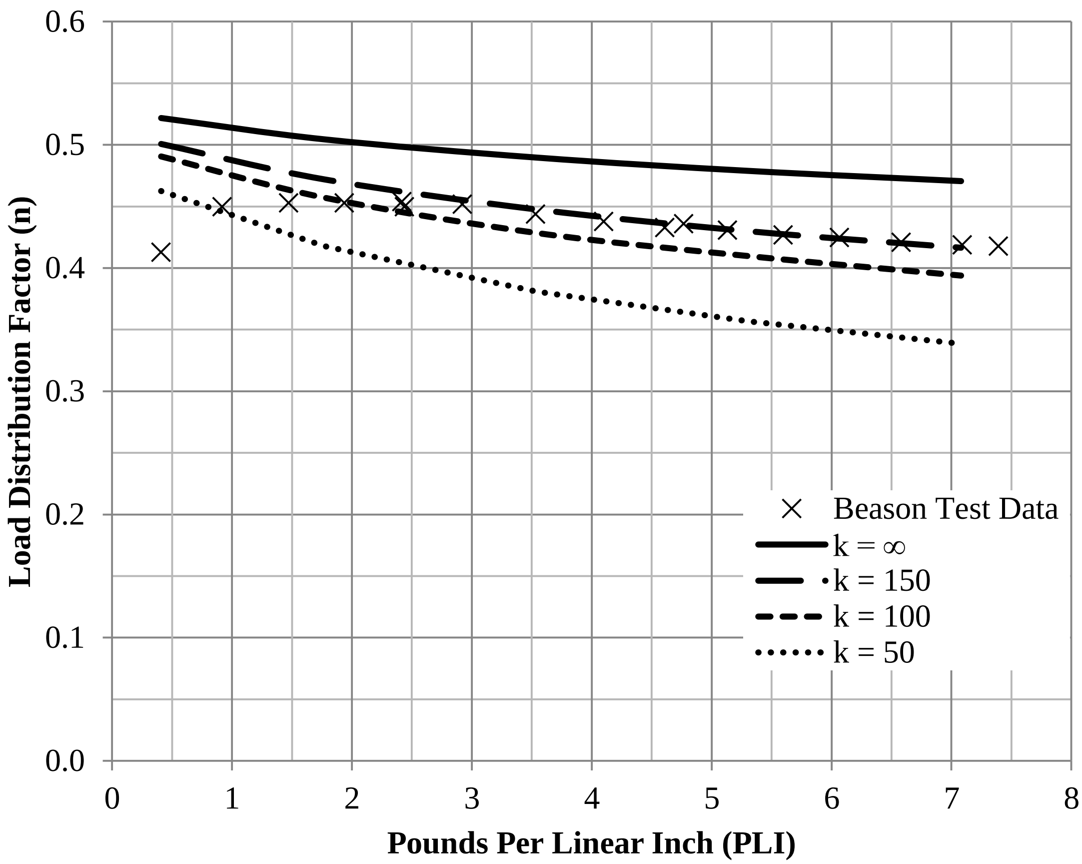

FIG. A - 3 Experiment C122 test result comparison with spacer flexibility

TABLE A - 4 Experiment C131 test parameters

Outer Plate Thickness	0.103 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.19 in.
Long Dimension	20.59 in.
Gas Space Thickness	0.415 in.

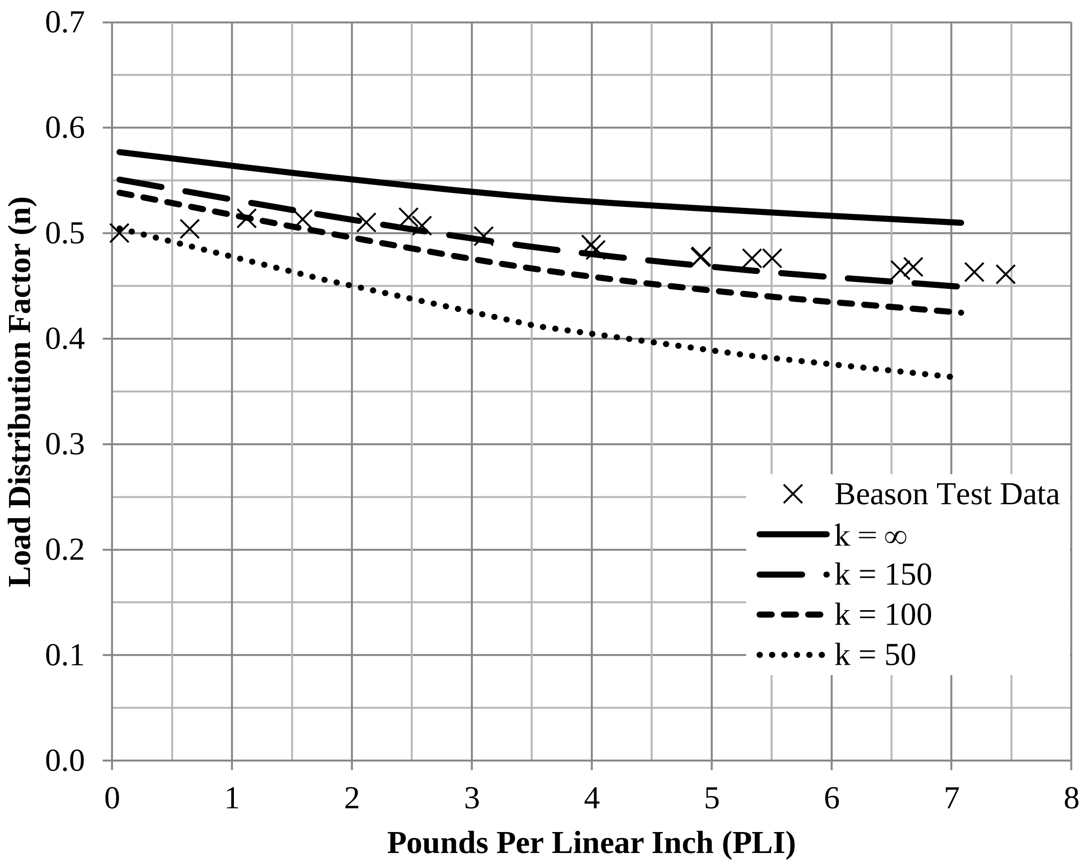

FIG. A - 4 Experiment C131 test result comparison with spacer flexibility

TABLE A - 5 Experiment C132 test parameters

Outer Plate Thickness	0.103 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.19 in.
Long Dimension	20.59 in.
Gas Space Thickness	0.415 in.

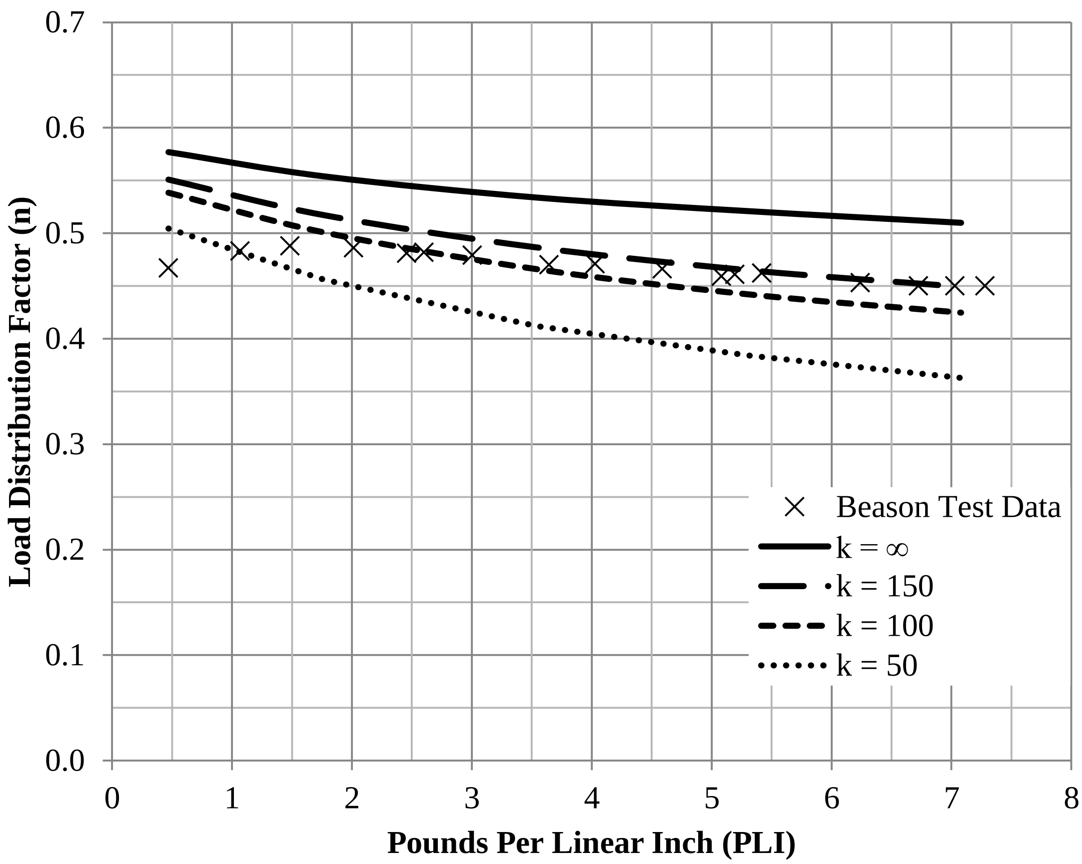

FIG. A - 5 Experiment C132 test result comparison with spacer flexibility

TABLE A - 6 Experiment C141 test parameters

Outer Plate Thickness	0.127 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.19 in.
Long Dimension	20.59 in.
Gas Space Thickness	0.415 in.

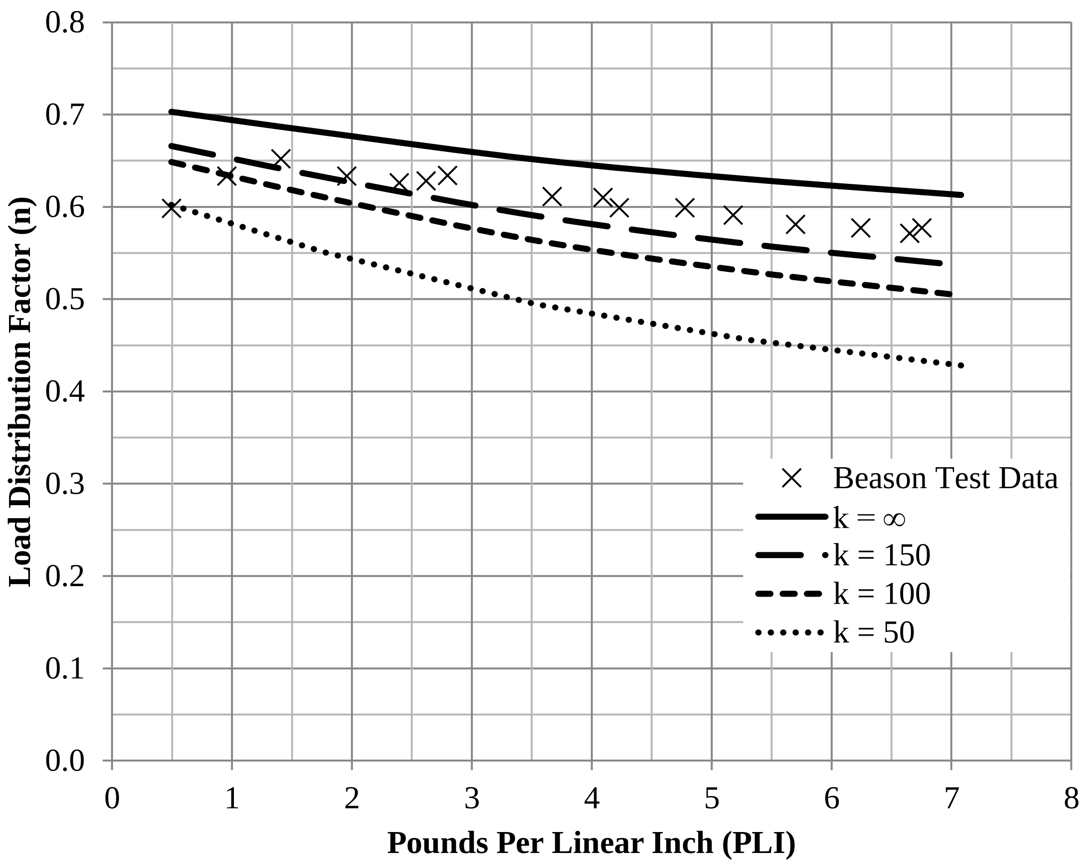

FIG. A - 6 Experiment C141 test result comparison with spacer flexibility

TABLE A - 7 Experiment C151 test parameters

Outer Plate Thickness	0.186 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.19 in.
Long Dimension	20.59 in.
Gas Space Thickness	0.415 in.

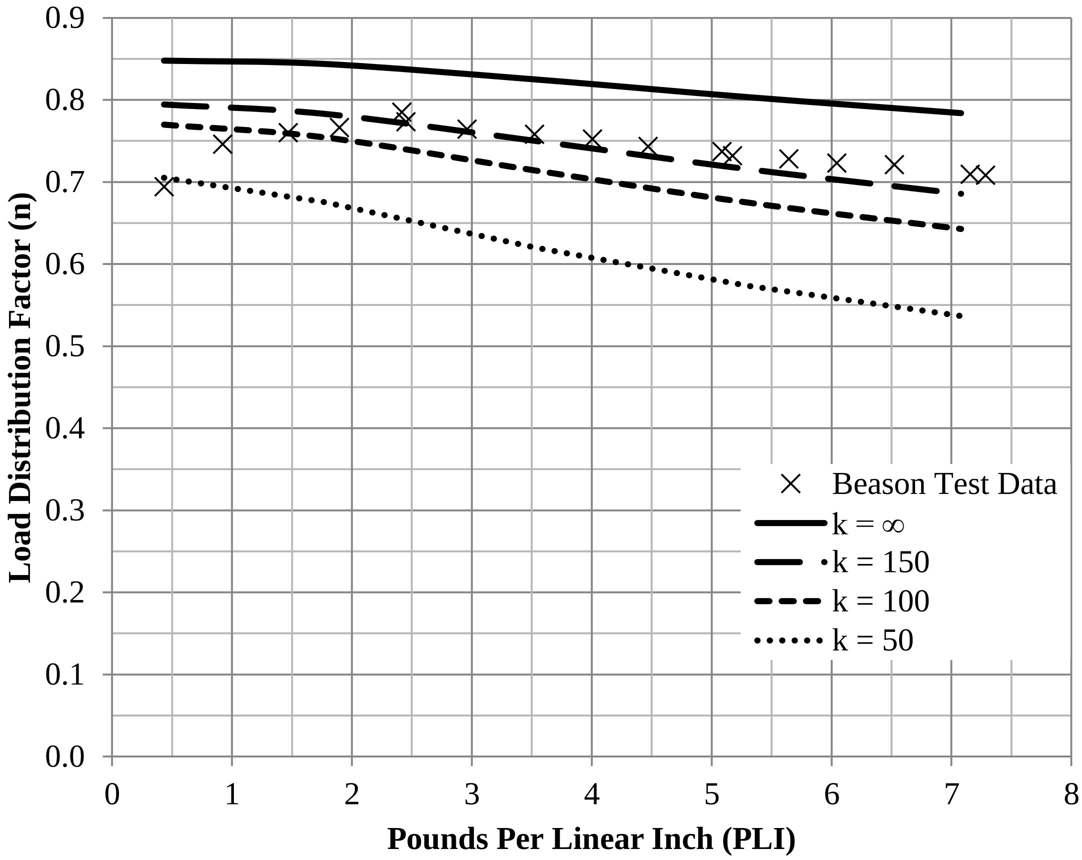

FIG. A - 7 Experiment C151 test result comparison with spacer flexibility

TABLE A - 8 Experiment C211 test parameters

Outer Plate Thickness	0.09 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	44.06 in.
Gas Space Thickness	0.415 in.

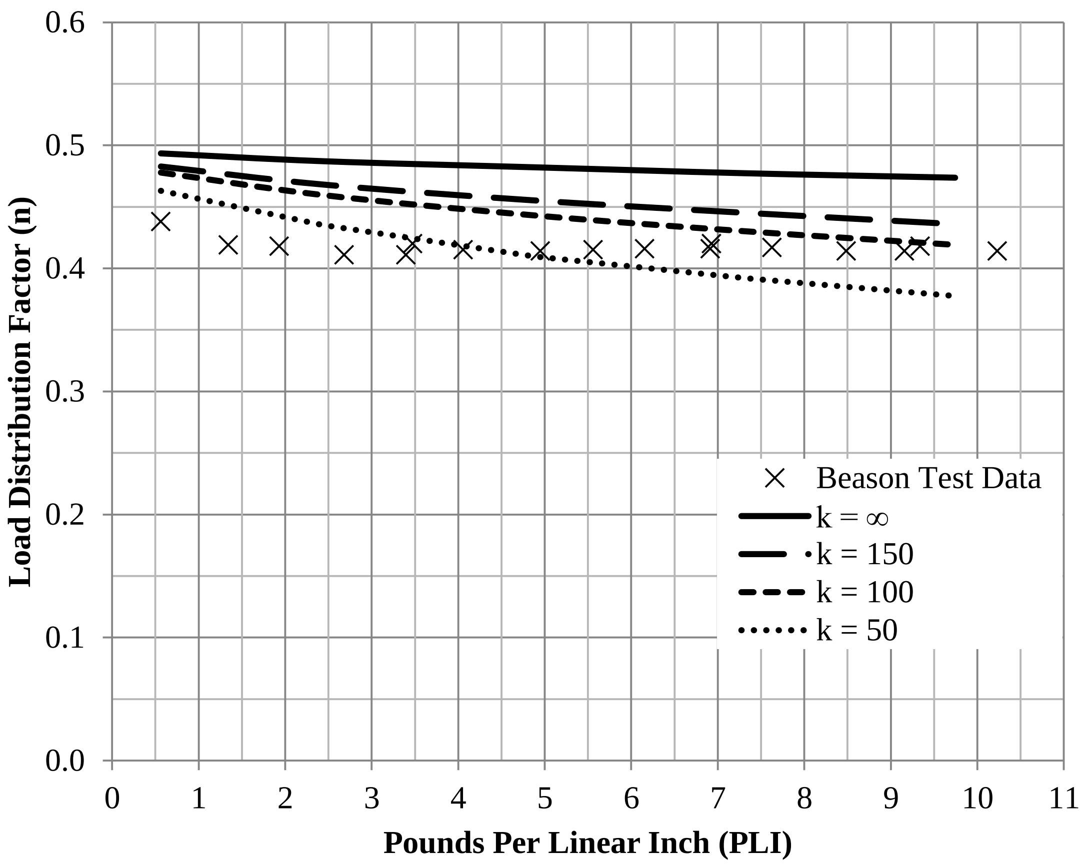

FIG. A - 8 Experiment C211 test result comparison with spacer flexibility

TABLE A - 9 Experiment C221 test parameters

Outer Plate Thickness	0.095 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	44.06 in.
Gas Space Thickness	0.415 in.

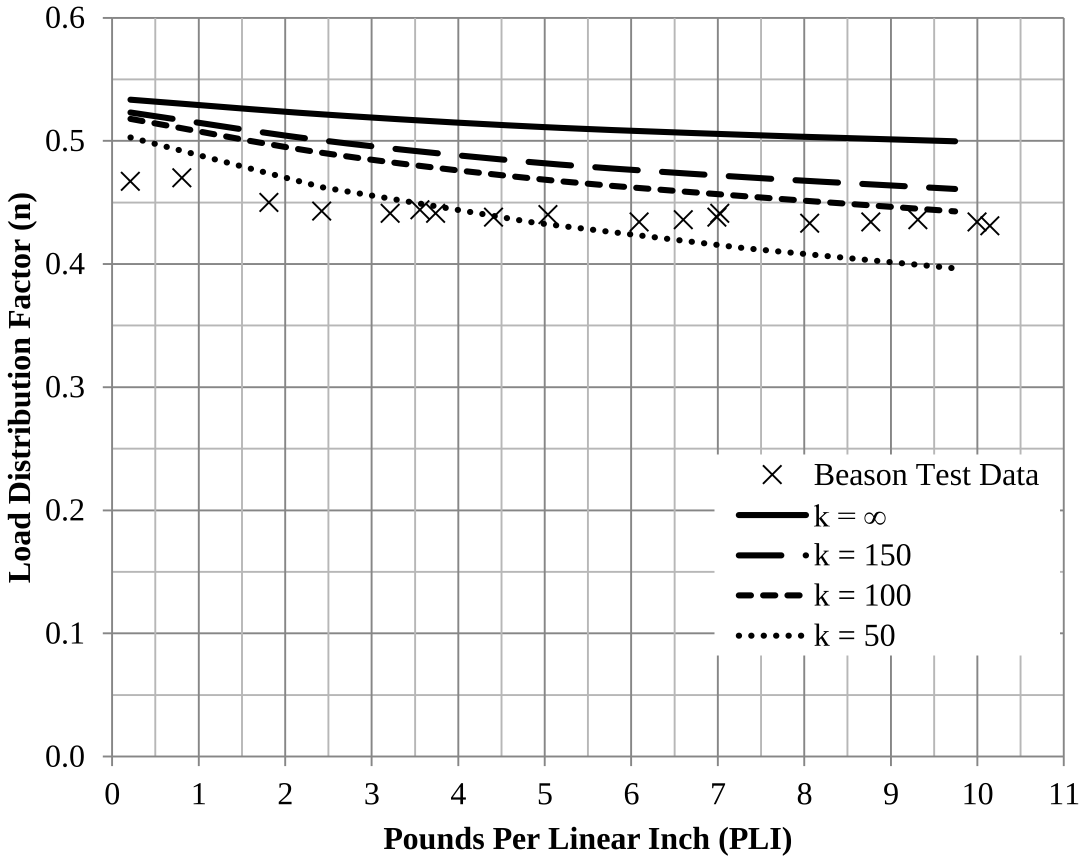

FIG. A - 9 Experiment C221 test result comparison with spacer flexibility

TABLE A - 10 Experiment C231 test parameters

Outer Plate Thickness	0.103 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	44.06 in.
Gas Space Thickness	0.415 in.

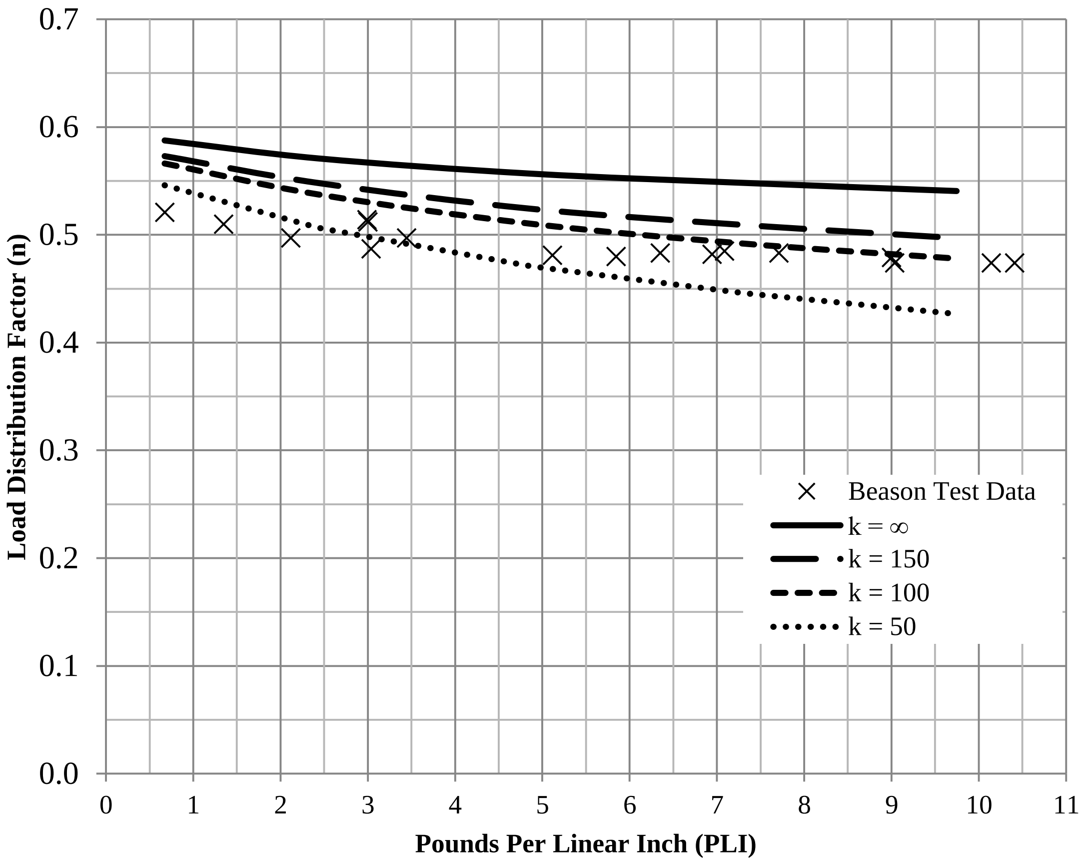

FIG. A - 10 Experiment C231 test result comparison with spacer flexibility

TABLE A - 11 Experiment C241 test parameters

Outer Plate Thickness	0.128 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	44.06 in.
Gas Space Thickness	0.415 in.

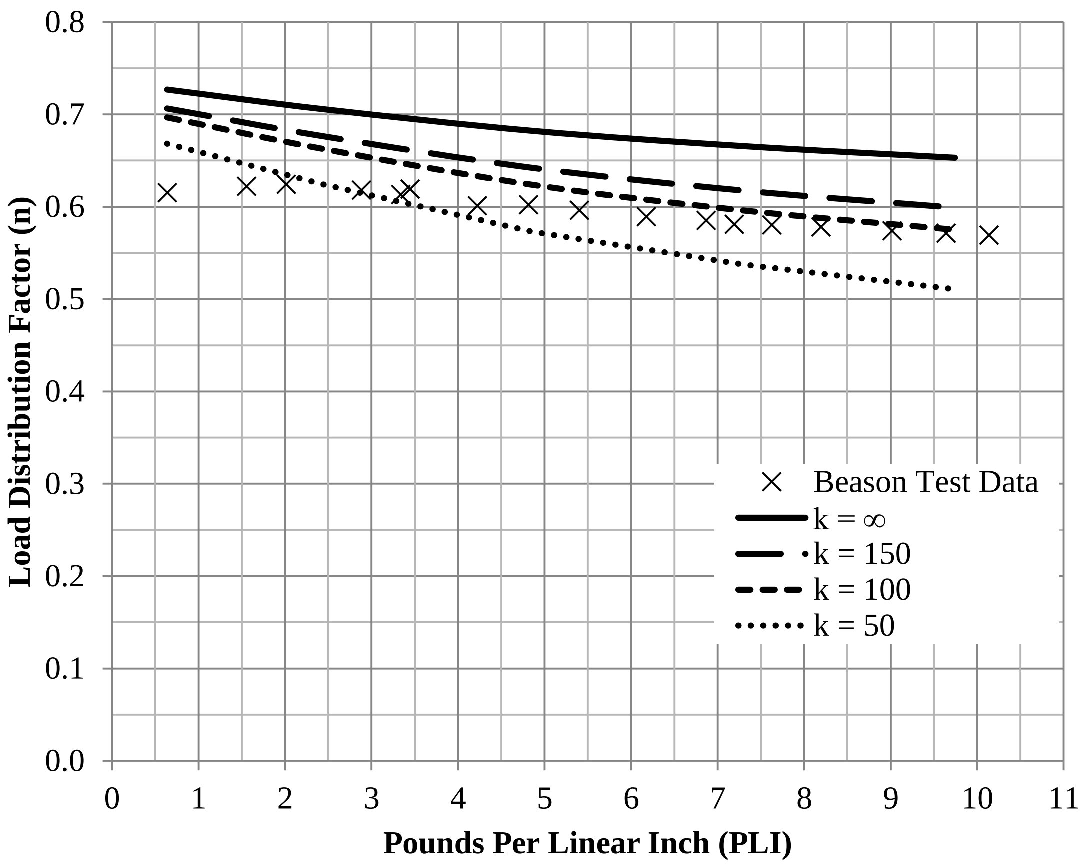

FIG. A - 11 Experiment C241 test result comparison with spacer flexibility

TABLE A - 12 Experiment C251 test parameters

Outer Plate Thickness	0.186 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	44.06 in.
Gas Space Thickness	0.415 in.

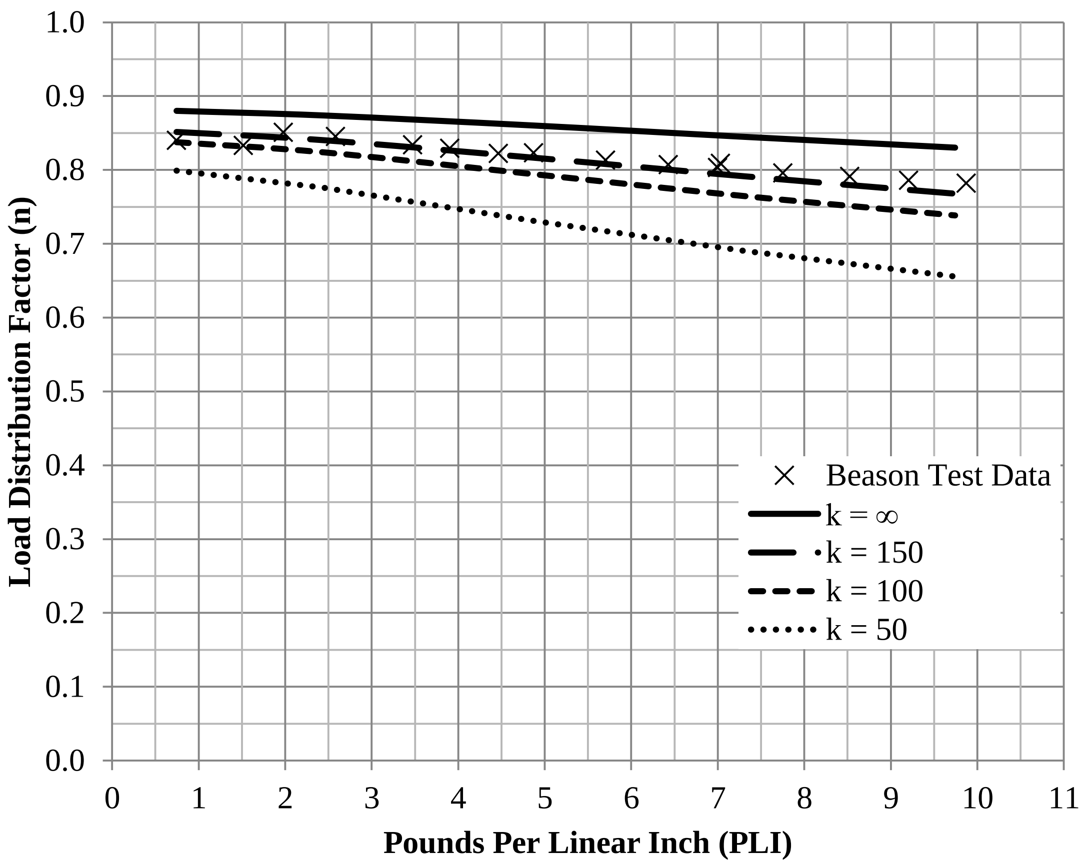

FIG. A - 12 Experiment C251 test result comparison with spacer flexibility

TABLE A - 13 Experiment C311 test parameters

Outer Plate Thickness	0.09 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	67.93 in.
Gas Space Thickness	0.415 in.

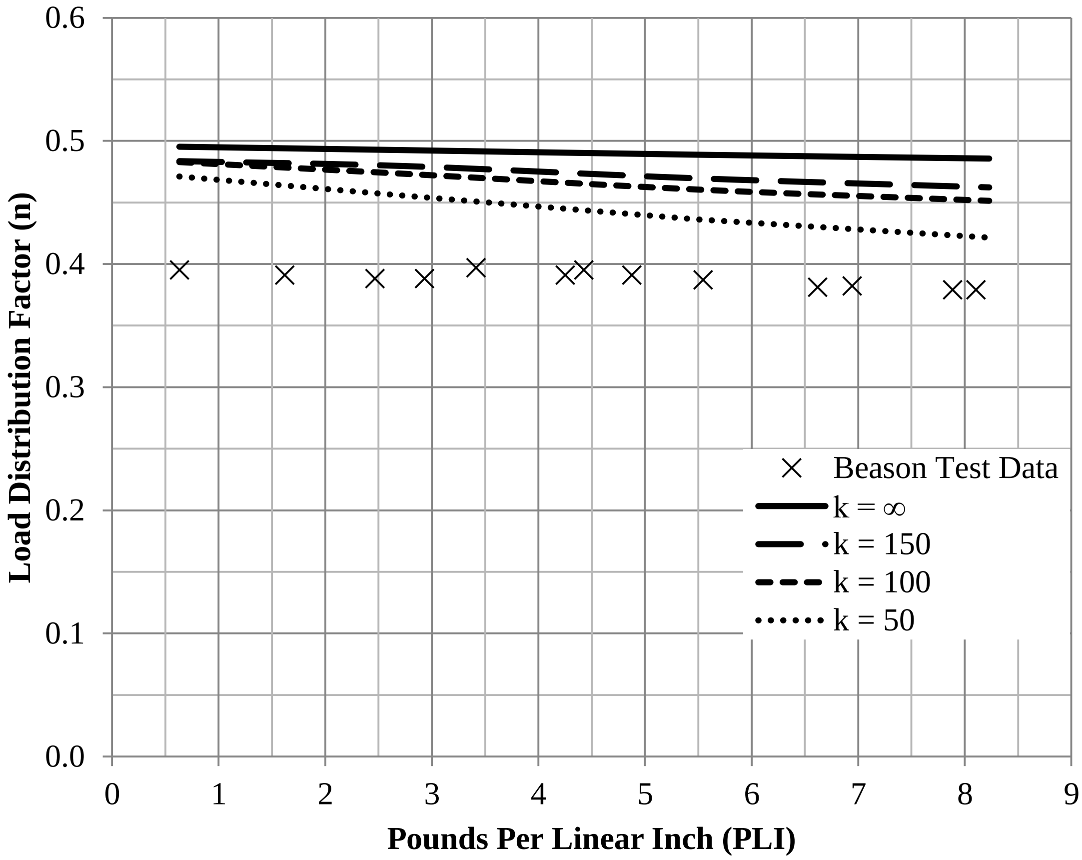

FIG. A - 13 Experiment C311 test result comparison with spacer flexibility

TABLE A - 14 Experiment C321 test parameters

Outer Plate Thickness	0.095 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	67.93 in.
Gas Space Thickness	0.415 in.

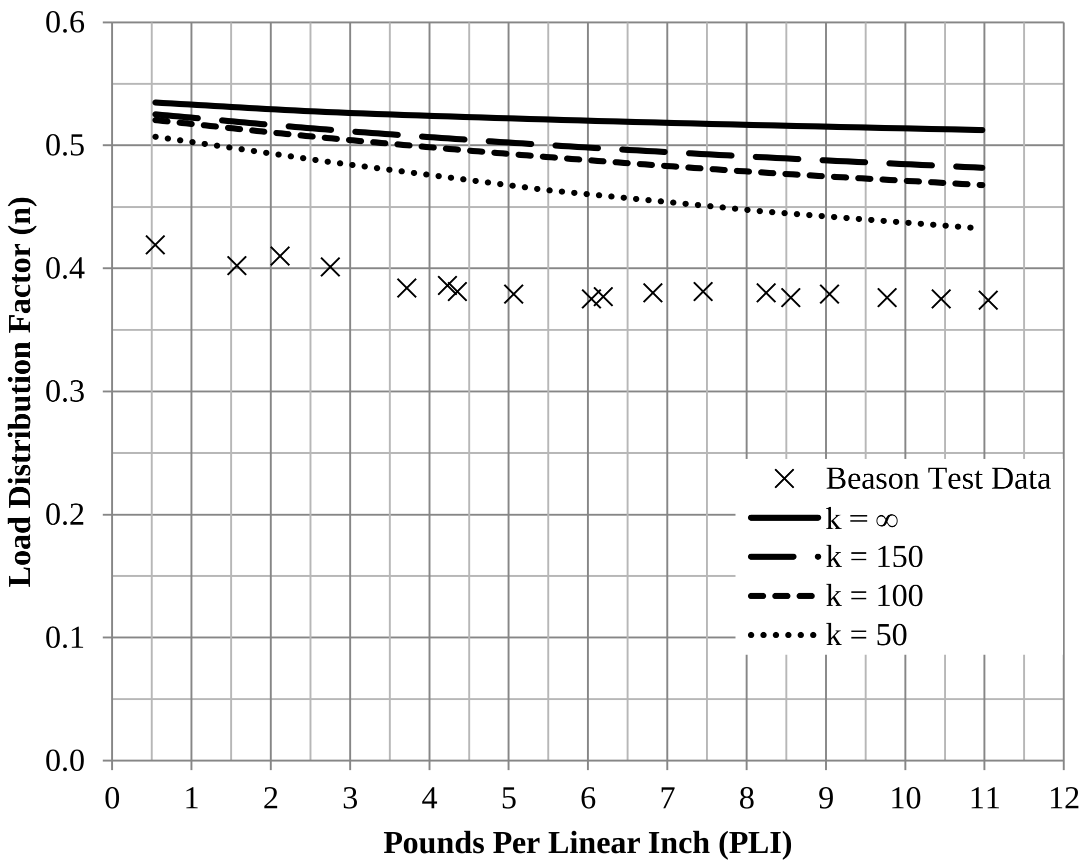

FIG. A - 14 Experiment C321 test result comparison with spacer flexibility

TABLE A - 15 Experiment C341 test parameters

Outer Plate Thickness	0.128 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	67.93 in.
Gas Space Thickness	0.415 in.

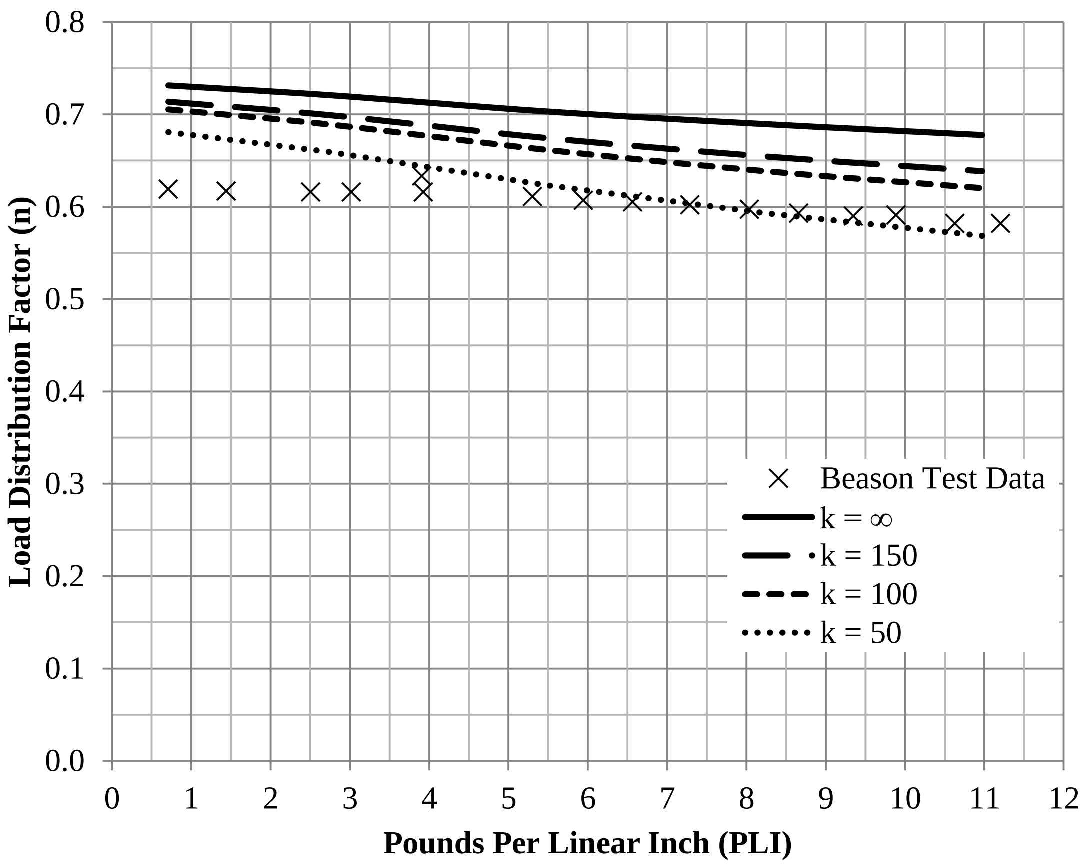

FIG. A - 15 Experiment C341 test result comparison with spacer flexibility

TABLE A - 16 Experiment C351 test parameters

Outer Plate Thickness	0.186 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	67.93 in.
Gas Space Thickness	0.415 in.

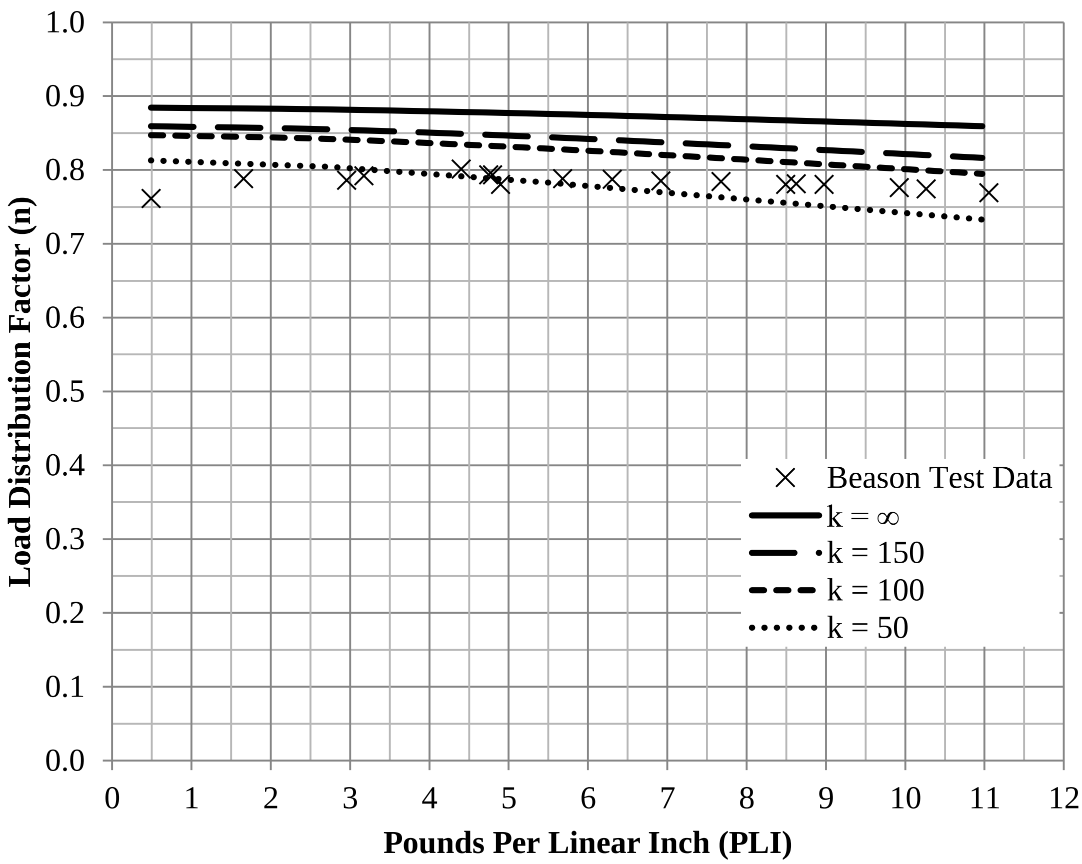

FIG. A - 16 Experiment C351 test result comparison with spacer flexibility

TABLE A - 17 Experiment C411 test parameters

Outer Plate Thickness	0.118 in.
Inner Plate Thickness	0.118 in.
Short Dimension	44.06 in.
Long Dimension	44.59 in.
Gas Space Thickness	0.360 in.

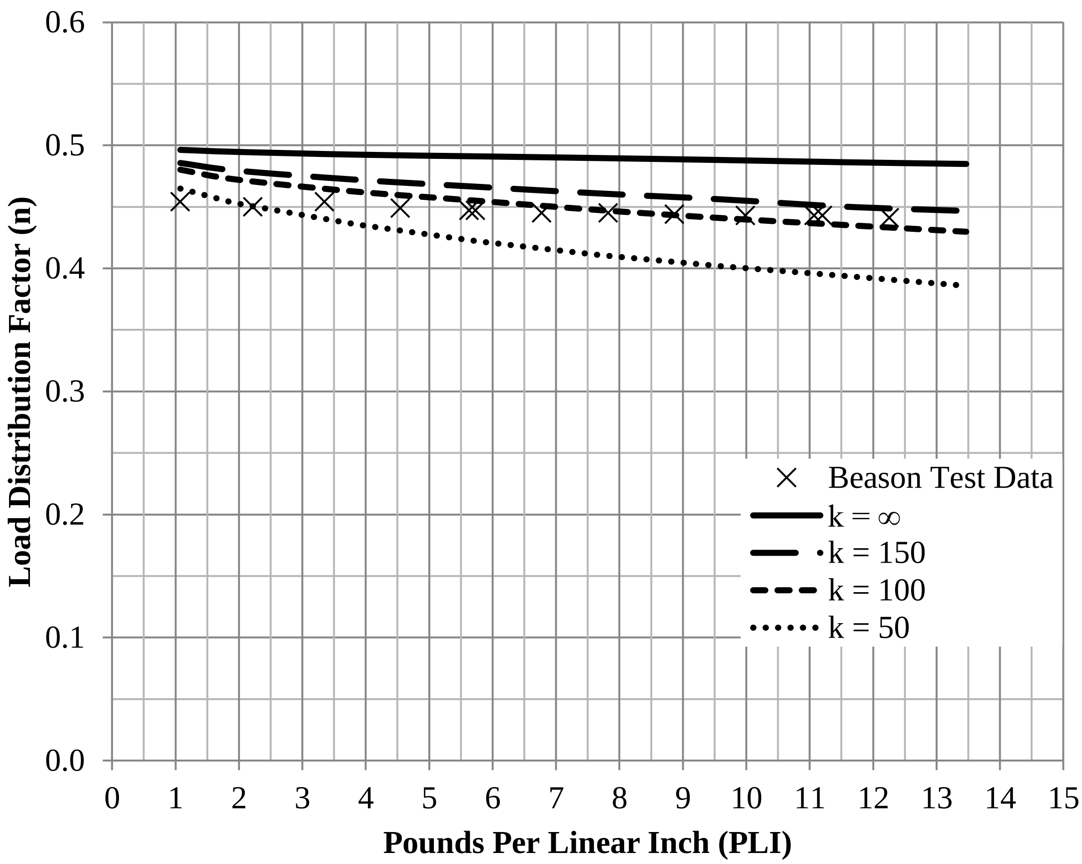

FIG. A - 17 Experiment C411 test result comparison with spacer flexibility

TABLE A - 18 Experiment C421 test parameters

Outer Plate Thickness	0.118 in.
Inner Plate Thickness	0.118 in.
Short Dimension	44.06 in.
Long Dimension	44.59 in.
Gas Space Thickness	0.710 in.

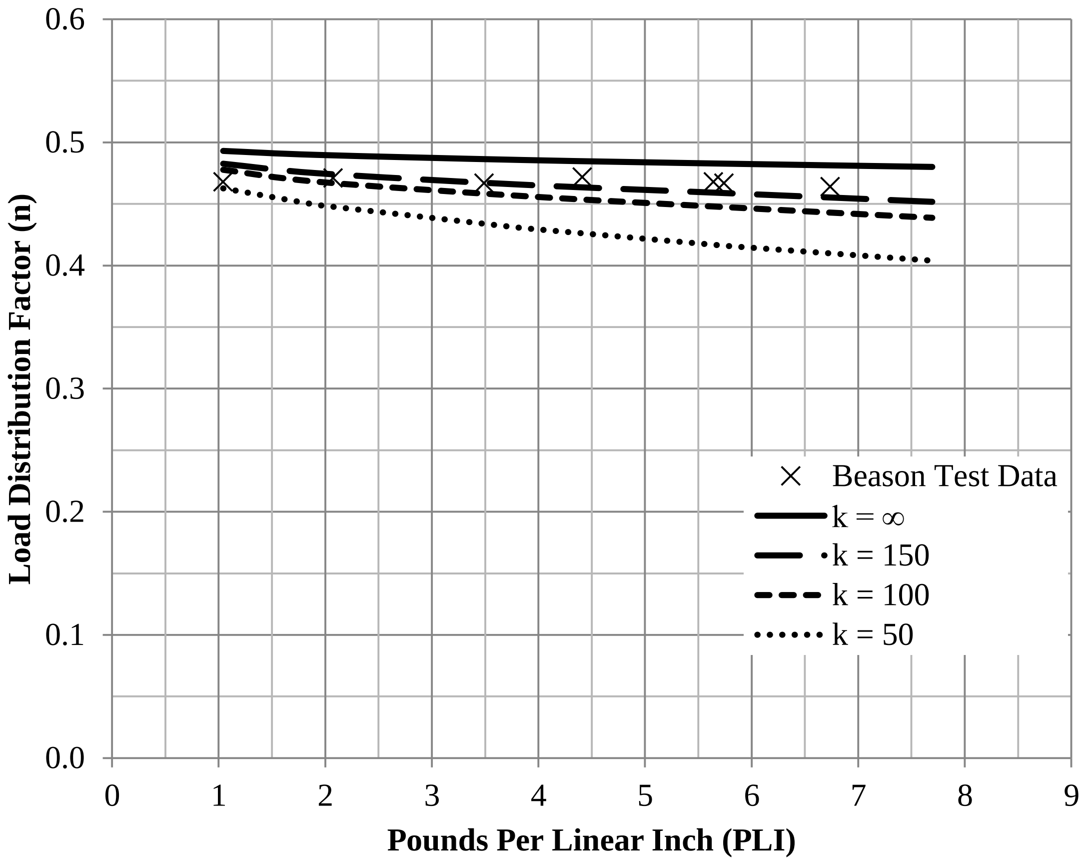

FIG. A - 18 Experiment C421 test result comparison with spacer flexibility

TABLE A - 19 Experiment C611 test parameters

Outer Plate Thickness	0.09 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.19 in.
Long Dimension	20.59 in.
Gas Space Thickness	0.415 in.

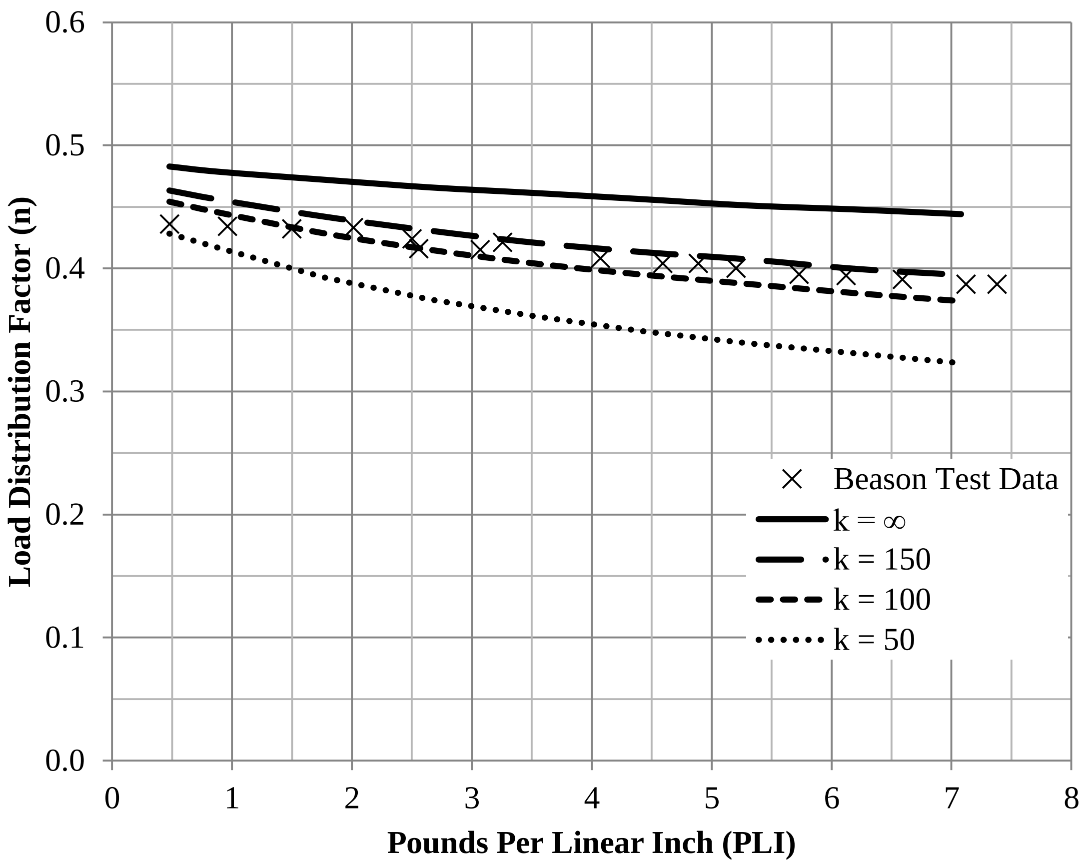

FIG. A - 19 Experiment C611 test result comparison with spacer flexibility

TABLE A - 20 Experiment C621 test parameters

Outer Plate Thickness	0.09 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	44.06 in.
Gas Space Thickness	0.415 in.

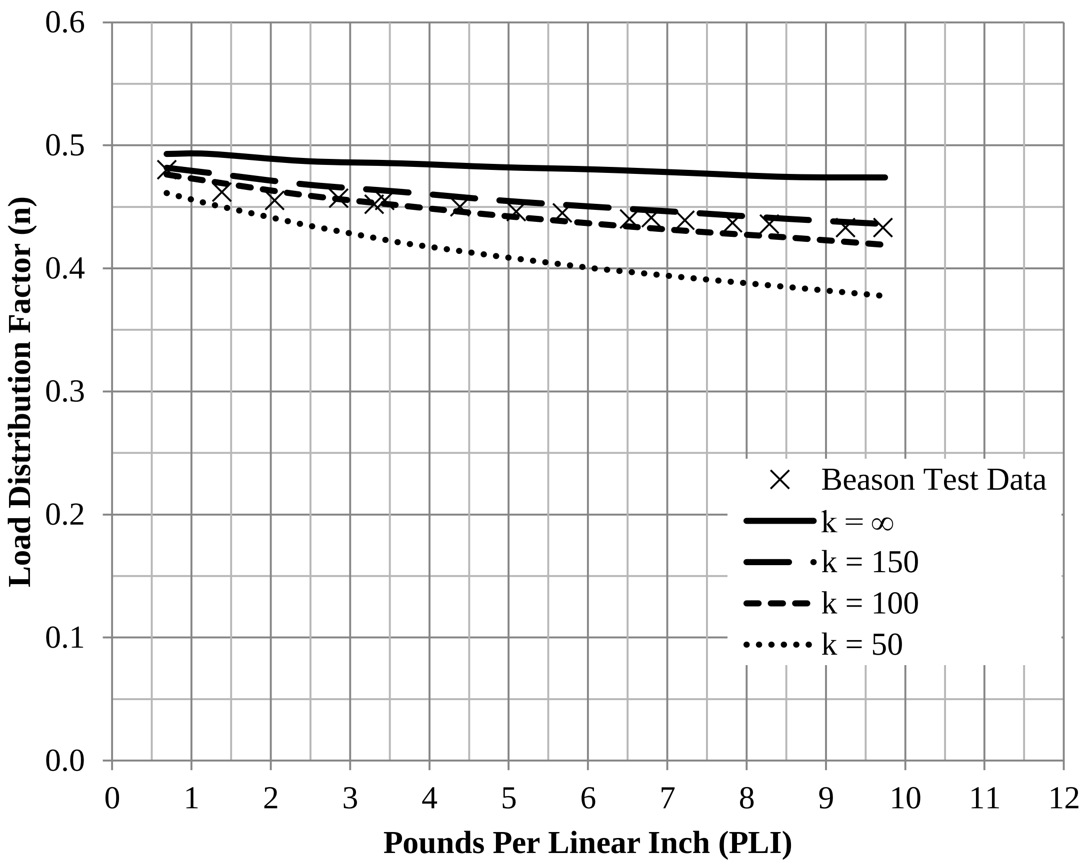

FIG. A - 20 Experiment C621 test result comparison with spacer flexibility

TABLE A - 21 Experiment C631 test parameters

Outer Plate Thickness	0.09 in.
Inner Plate Thickness	0.09 in.
Short Dimension	20.59 in.
Long Dimension	67.93 in.
Gas Space Thickness	0.415 in.

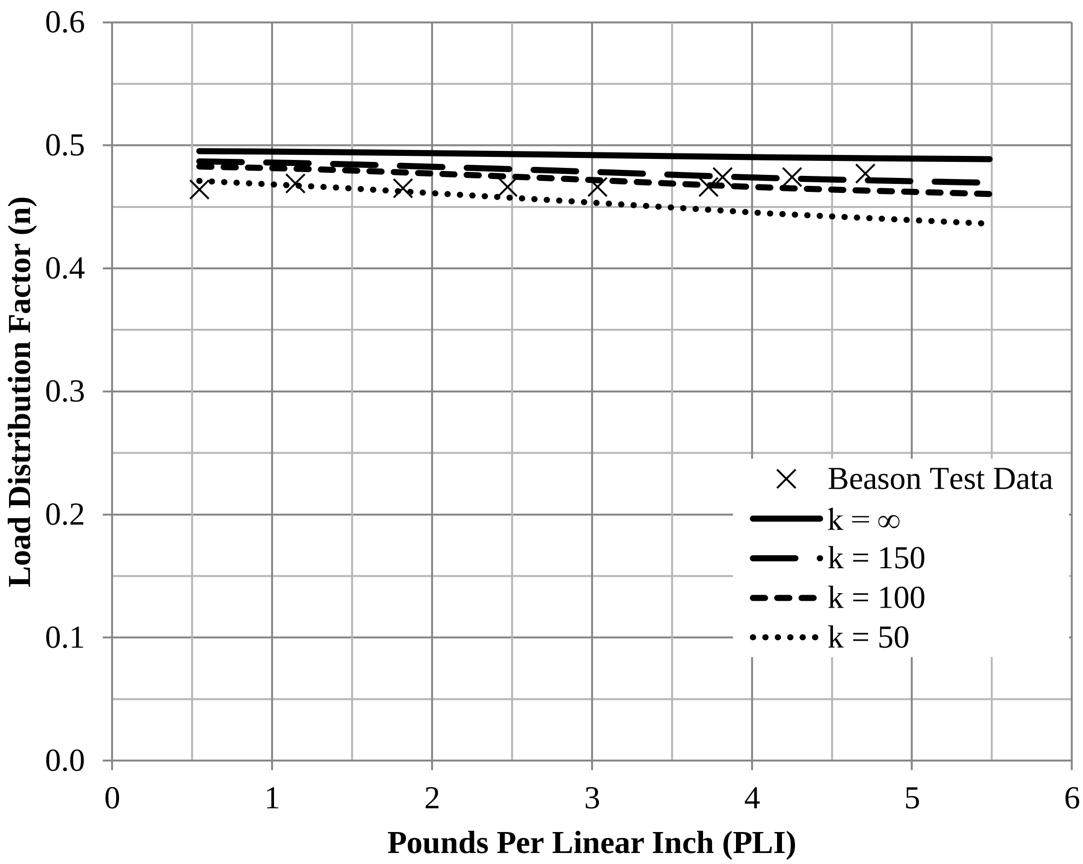

FIG. A - 21 Experiment C631 test result comparison with spacer flexibility