To the Graduate Council

I am submitting herewith a thesis written by Shannon Kirk McKamey entitled "Analysis and Optimization of Lightweight Foundations for Portable Equipment." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

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ANALYSIS AND OPTIMIZATION OF LIGHTWEIGHT FOUNDATIONS FOR PORTABLE EQUIPMENT

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Shannon Kirk McKamey
August 2001

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DEDICATION

This thesis is dedicated to my parents

Mr. Gleason Woodrow McKamey

and

Mrs. Shirley Ann McKamey

For their constant support and dedication to helping me fulfill my dreams

ACKNOWLEDGMENT

I would like to thank my academic and thesis advisors, Dr. David W. Goodpasture and Dr. James H. Deatherage for their support during the development of this thesis. I would also like to thank the remaining members of my graduate committee, Dr. Edwin Burdette and Dr. Mike Jackson.

I am grateful to the management of Astec, Inc., for their support. Astec, Inc. is the nation's leader in the production of asphalt equipment. Their facilities and patience were essential for this research. I acknowledge and offer special thanks to Earl Edwards and Malcolm Swanson of Astec, Inc. Thanks to Mike Varner for helping me during the construction phases of my research. I also offer a special thanks to Donnie Needham for his assistance in material preparation.

I acknowledge and thank Rick Hutmacher of Kolberg-Pioneer for his help during the stress analysis research portion of this document. Rick spent valuable time helping me understand the intricacies of DesignSpace©, which was one of the computer aided stress analysis packages used in the initial analysis. A special thanks to Randy Rainwater for his help during laboratory tests.

ABSTRACT

The research presented in this document was conducted to identify the optimum design and layout of small foundations known as landing pads. The ultimate goal of this research was to compare the stress performance of varying styles of pads and to determine the best design. It was also important to develop a foundation that was aesthetically pleasing.

Experiments were performed in the shop of Astec, Incorporated and on the campus of the University of Tennessee, Knoxville to determine an "ideal" shape and examine its structural integrity. Development of these "idealized" shapes was initiated by performing basic structural analysis on popular shapes currently utilized in the industry. Basic structural analysis consisted of the following :

- Mathematical estimation of deflection for an isolated cross-section and span length
- Calculating bending stress with the use of shear and moment diagrams for isolated sections
- Mathematical estimation of shear stress for an isolated cross-section

Determination of an optimum shape was done by performing laboratory experiments and utilizing stress analysis software. For laboratory experimentation, these shapes were re-created by constructing polyvinyl chloride (PVC) models. The models were built to scale and were tested under loading conditions simulating loads applied from portable equipment. The main purpose of these tests was to visually examine the effects and behavior of the pad under load and to determine maximum stresses through the use of strain gages. Displacement was measured in the laboratory with dial gages and compared to design criteria for deflection limits. Comparisons of behavior between PVC and steel were taken into account with the use of stress analysis software also. This was necessary to predict the behavior of the PVC models and provide validity for the software results.

The selected shapes were created in a well known stress analysis software package known as STAAD/Pro©. The stress analysis modeler in STAAD/Pro© allowed the simulation of real world testing outside of the laboratory. The models were given properties for both A36 Carbon Steel and PVC. The models were analyzed by applying static loads, which represented both equipment weight and the overturning moment due to wind.

Research revealed that the performance of the landing pads depended on subgrade conditions. The ultimate load for each landing pad increased as the stiffness of the subgrade increased. Of the three landing pads with only four stiffeners, the triangular stiffened landing pad performed the best. Ultimately, the STAAD/Pro© software provided results that were consistent with the basic structural analysis methods and the strain gage testing methods used in the laboratory. The laboratory research was not a very effective comparison to the values obtained in the computer aided stress analysis, however. Strain gage locations were determined initially with Ansys DesignSpace©. However, boundary conditions were initially incorrect, so strain gages were not pinpointed at the areas of highest stress. Deflection properties were proportional and relatively small in all pads, and the research and did not determine a clear-cut choice as to which pad should be used.

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DEFINITIONS

Amorphous – Used to describe a non-crystallized material with no regularity in the arrangement of its molecular constituents.

Elastic – Capable of sustaining stress without permanent deformation: the term is also used to denote conformity to the law of stress-strain proportionality. An elastic stress or strain is a stress or strain within the elastic limit.

Isotropic – Pertaining to strength of materials, isotropic usually means having the same strength and elastic properties (modulus of rigidity, modulus of elasticity and Poisson's ratio) in all directions.

Modulus of Elasticity – The rate of change of unit tensile or compressive stress with respect to unit tensile or compressive strain for the condition of uniaxial stress within the proportional limit. For most materials, the modulus of elasticity is the same for both tension and compression. For nonisotropic materials such as wood, it is necessary to distinguish between the moduli of elasticity in different directions.

Plasticity – The property of sustaining appreciable (visible to the eye) permanent deformation without rupture. The term is also used to denote the property of yielding or flowing under steady load.

Poisson's ratio – The ratio of lateral unit strain to longitudinal unit strain under the condition of uniform and uniaxial longitudinal stress within the proportional limit of the stress-strain curve.

Proportional limit – The greatest stress that a material can sustain without deviating from the law of stress-strain proportionality.

Ultimate Strength – The ultimate strength of a material in tension, compression, or shear, respectively, is the maximum tensile, compressive, or shear stress that the material can sustain calculated on the basis of maximum load.

Strain – relative change in shape or size of an object due to externally applied forces. A stretch is a tensile strain; a shortening is a compressive strain; and an angular distortion is a shear strain.

Stress – the internal unit force acting upon an object relative to strain.

Stress-strain diagram – the curve obtained by plotting unit stresses as ordinates against corresponding unit strains as abscissas.

Yield strength – The stress at which a material exhibits a permanent deformation or set.

CHAPTER 1

INTRODUCTION

1.1 Background

An integral part of the development of portable equipment is the development of its infastructure and support system. In order to successfully support portable equipment on a multitude of surfaces, it is necessary to provide a support system capable of withstanding the loads applied to the system and one which does not permanently deform the foundation upon which it rests. For these reasons, the goal is to construct an interchangeable, lightweight structure that is compatible with all types of equipment and also compatible for all subgrades or foundations.

The ideal system should provide a lightweight support, with minimum labor and equipment costs to construct. The system should easily mount to the equipment and should not interfere with operations of the equipment, or with working conditions surrounding the equipment.

1.2 Types of Landing Pads

Landing pads are common on all types of equipment. Excavators and cranes are fortified with landing pads to provide stability and adequate support during digs and heavy lifting. Landing pads come in all shapes and sizes based on the size and application of the equipment. Typically, the size of the landing pad and the material thickness of its components are directly proportional to the weight of the equipment and the loads to be applied. Special applications consider the conditions of the sub-

base or foundation that will lie beneath the pad. For the case in this research, varying foundation conditions are discussed since landing pads are typically associated with temporary placement and may be needed anywhere. Thus, an optimum, universal design for all types of subgrades or foundations is the goal. Figure 1.1 illustrates some of the different types of landing pads used in the industry today.

The principal concept in determining optimum design for a landing pad is to provide a stable structure with enough surface area to adequately support the weight

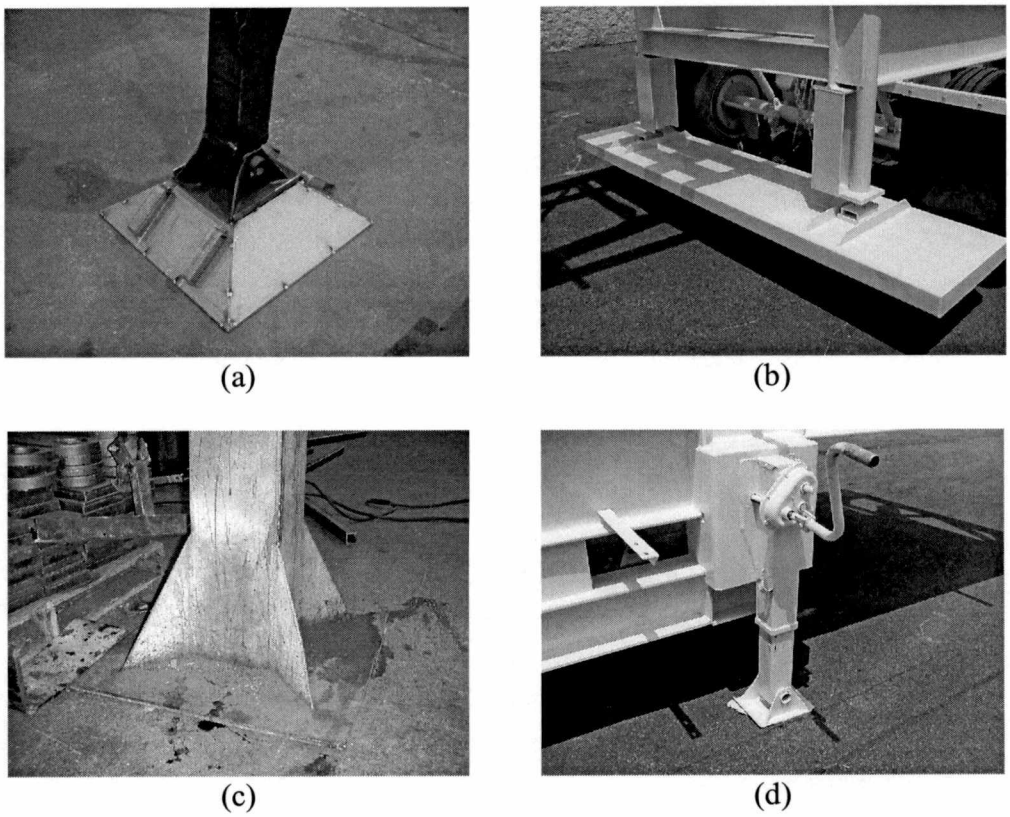


FIGURE 1.1
Illustrations of commonly used landing pads for portable equipment
(a) retractable mount binkley atop landing pad, (b) long retractable pad, (c) shop landing pad, (d) retractable mount binkley w/o landing pad

of the equipment and forces induced by wind without "punching through" or causing bearing capacity failure of the foundation. It is also necessary to consider the stresses in the steel used in construction. Basically, the landing pad changes a point load, which can be harmful to the foundation, into a small-distributed load, which will reduce the impact on the foundation.

1.3 How a Landing Pad Works

A landing pad serves as a load distributor for a load-carrying compression member. Much like increasing the diameter of a column reduces punching shear in a floor slab, when the size of the area making contact with a surface is increased and load is kept at a constant, the subgrade is protected. Increasing the surface area reduces the ability of the primary load-carrying member to punch through, or penetrate the surface. Figure 1.2 demonstrates the technique of load distribution in an ideal subgrade condition. It does not take into account variances in load distribution caused by the addition of a moment to the axial load.

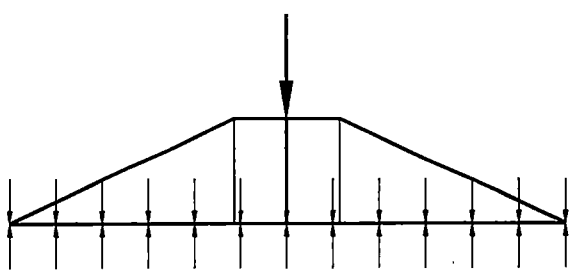


FIGURE 1.2
Ideal load distribution diagram for a landing pad

It is a relatively simple process to determine the loads that have to be handled by a landing pad. In addition to the dead and live loads of the equipment, loads induced by the overturning moment due to wind forces should be taken into consideration. The downward force resulting from a couple force induced by wind should be included for the pad. Dead load should exceed the upward force of the couple so that no uplift is encountered. If uplift is encountered during design, then the equipment must be anchored to prevent overturning. Design to accommodate seismic forces can be neglected since the equipment is portable; in some cases, industries neglect wind forces also. Information on determining wind loads can be found in the Uniform or Standard Building Codes. Beyond dead and live loads, the manufacturer of the equipment should determine the criteria for which a landing pad is to be designed. Figure 1.3 below demonstrates how wind forces affect the design of a landing pad (Das, 1990).

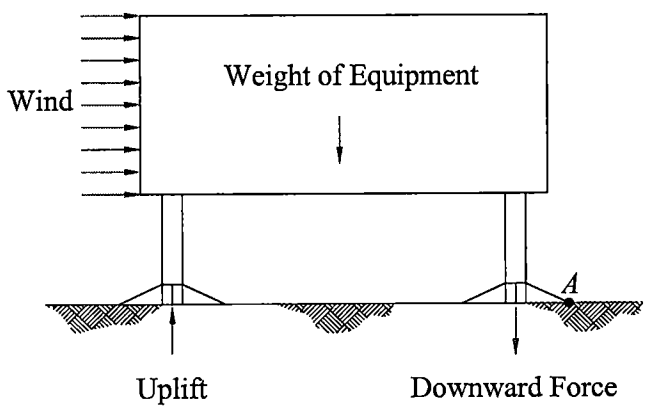


FIGURE 1.3
Diagram of couple force resulting from wind pressure

1.4 Objective of Study

Two different approaches to providing adequate design are to either size the landing pad according to the corresponding loads or place landing pads of a known capacity in enough locations to support the load. The objective of this investigation was to determine what style of landing pad has maximum load-carrying ability through research, basic structural analysis, field-testing, and finite element analysis (FEA). These methods were used to determine the optimum design as it pertains to stress performance. These criteria are typically used to design most structures in use today. Ease of construction, which is directly related to cost, should be taken into consideration also.

The ideal landing pad design provides a structure that is aesthetically pleasing to the eye while sustaining the necessary loads. The resulting structure does not visibly deform under load, does not create a collection point for ponding water, and does not fail due to stress. Other circumstances should also be addressed such as the amount of labor needed to construct the pad. This investigation examines several different shapes with varying subgrade conditions, but keeps material amounts at a constant.

Figure 1.4 illustrates a typical landing pad. The baseplate of the pad is not designed to be a primary load-carrying member of the structure, but rather the contact surface. The baseplate should be a flat, level surface so that the pad can rest in complete contact with a relatively stable and compacted surface. The stiffening

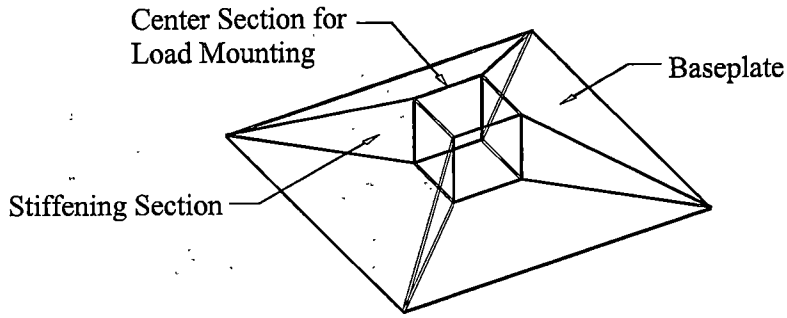


FIGURE 1.4
Components of a landing pad

sections, which are cut from steel plate, are designed to be the main load carrying members. The increase in stiffener height at practically any location strengthens the pad to varying degrees, similar to increasing the depth of a beam to make it stronger.

CHAPTER 2

SELECTION OF MODEL SHAPES

2.1 Introduction

There are many different varieties of landing pads used in today's industry. Each pad is sized and shaped based on loading requirements and application. The initial selection of size and style for the landing pads in this research was a complicated process. The evaluation of the landing pad shape is not easily obtained using hand calculation techniques. The initial selection was performed based upon simple structural analysis, field observation and common sense. For the most part, the size and type of material used were not as important as the consistency of the design. Each pad shape was constructed with the same amount of material and out of material with the same thickness.

2.2 Simple Structural Analysis Techniques

It is difficult to mathematically predict how a landing pad will behave when subjected to a compressive load. A simple but effective approach is the isolation technique. The pad is subdivided into small strips to simplify the analysis. This process treats the small section as a simple beam. This method does not take into account the interaction of stresses and displacements beyond the edges of the strip. Finite Element Analysis (FEA) was necessary to determine the "true" stress and deflection throughout the surface of the pad. FEA programs allow the user to obtain more accurate results since stresses are translated through the pad with the use of tiny

meshing stress elements. The elements are connected to one another and affect the behavior at different nodes.

Figure 2.1 shows a strip of the plate subjected to bearing pressure load without any stiffening sections. In the scenario used in this experimentation, the baseplate bottom was supported with springs and the load was applied at the top section. Once the shear and moment diagrams were calculated, the placement of the stiffeners was needed when stresses increased at a particular location of the pad. Reinforcement is provided by either adding stiffener depth for an increased moment of inertia, the easiest way to increase strength, or by strategically rearranging the stiffeners, which is more difficult.

When shear and moment diagrams were constructed for the section in Figure 2.1, the maximum shear and bending moments were found to occur at the supports. The supports in this example were located at the outside of the tallest section of the pad. Based on this diagram, it was easy to identify that the stiffener depth should be increased at the support to reduce the highest values of stress. This diagram

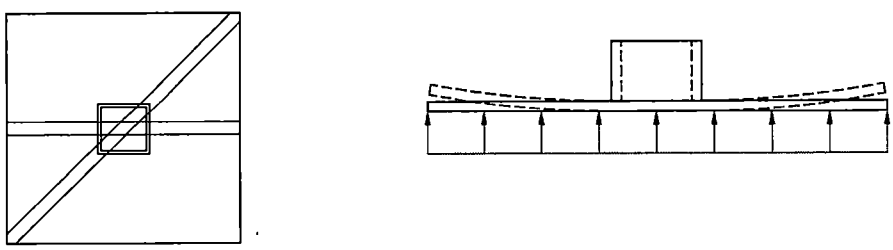


FIGURE 2.1
Section of un-reinforced landing pad under bearing pressure load

indicates that triangular stiffeners increasing in height towards the support are more effective.

Visual representations of the landing pads used in computer aided stress analysis and laboratory testing are shown in Figure 2.2. Details on the landing pad dimensions are represented in Table 2.1. These four pads were thoroughly examined for stress performance and deflection both in the laboratory and by FEA analysis. Their overall strength performance was the basis for selection of the optimum design, which is discussed in chapter 8.

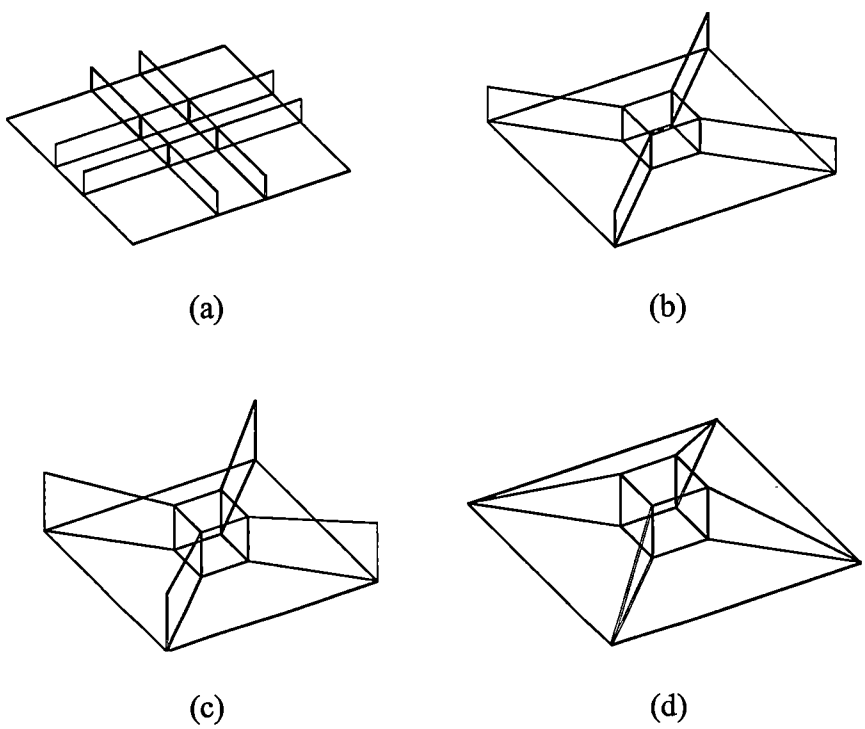


FIGURE 2.2
Cad rendering of models used in testing
(a) Landing Pad No. 1 (8 Rectangular Stiffeners), (b) Landing Pad No. 2 (4 Rectangular Stiffeners), (c) Landing Pad No. 3 (4 Parallelogram Stiffeners), (d) Landing Pad No.4 (4 Triangular Stiffeners)

TABLE 2.1
Landing pad model dimensions

Landing Pad #	Landing Pad Item	Item Dimensions (in)	Item Area (in^2)	Total Area (in^2)
1	Baseplate (square)	18 x 18	324	
	Stiffeners (rectangular)	8 @ 7 x 2	112	
	Loading Section	4 @ 4 x 2	32	468
2	Baseplate (square)	18 x 18	324	
	Stiffeners (rectangular)	4 @ 2.61 x 9.81	102	
	Loading Section	4 @ 2.61 x 4	42	468
3	Baseplate (square)	18 x 18	324	
	Stiffeners (parallelogram)	4 @ (2 & 3.71) x 9.81	112	
	Loading Section	4 @ 2 x 4	32	468
4	Baseplate (square)	18 x 18	324	
	Stiffeners (triangular)	4 @ 4.04 x 9.81	79	
	Loading Section	4 @ 4.04 x 4	65	468

CHAPTER 3

IMPORTANT MATERIAL PROPERTIES

3.1 Introduction

Landing pads utilized in the industry are typically constructed of steel. This investigation was performed with polyvinyl chloride (PVC) models in the laboratory, and with both PVC and steel models in the finite element analysis.

3.2 Overview of Steel Properties

Yield strength was used as the design criterion for maximum allowable load during development of the landing pads. The steel type used in this research was American Society for Testing and Materials (ASTM) A36 Carbon Steel with a minimum yield stress of 36 ksi. ASTM A36 is an all purpose carbon grade steel and is widely used in building and bridge construction. The stress-strain curve for A36 steel is shown in Figure 3.1.

Modulus of elasticity or Young's modulus is a fundamental material constant and is an index of the stiffness of a material. The modulus of elasticity for ASTM A36 steel is approximately 29×10^6 psi.

3.3 Behavior of Polyvinyl Chloride (PVC)

PVC has an amorphous molecular structure, which allows it to conform to ground settling and irregular subgrades without yielding. Because it is not a crystalline structure like the other harder plastics, PVC has a low modulus of elasticity and no yield point. In other words, the material will fail or crack suddenly

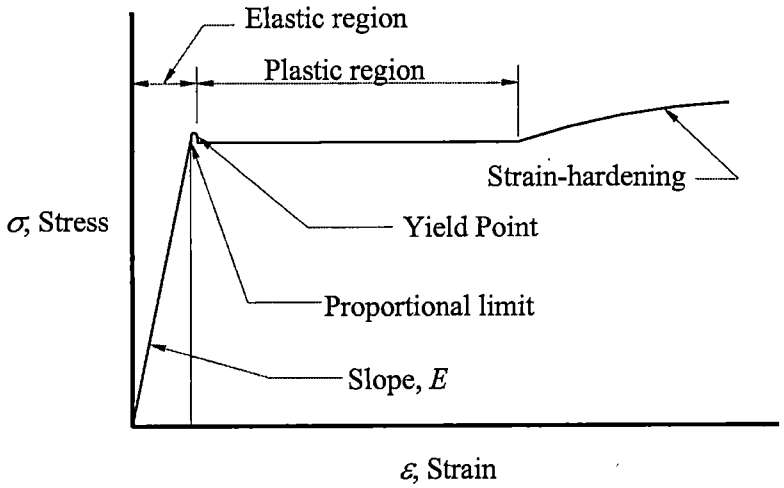


FIGURE 3.1
General stress-strain diagram for A36 steel

without demonstrating a plastic region where there is an increase in strain without an increase in stress. This behavior simplifies work in the laboratory because a completely linear relationship between stress and strain occurs. Due to the absence of inelastic behavior, it is simple to read the gage on the strain meter. Figure 3.2 shows a typical stress-strain curve for PVC.

By examining PVC models, it was possible to compare results that would occur in steel since the PVC is also an elastic material. In the elastic region, PVC behaves similarly to steel, but is not nearly as strong. Thus, it was much easier to test PVC pads to stress failure with the equipment provided. A well-constructed, steel landing pad would have been difficult and more dangerous to test to failure. Table 3.1 identifies some important properties for PVC and steel used in modeling (Heiberger, 1986).

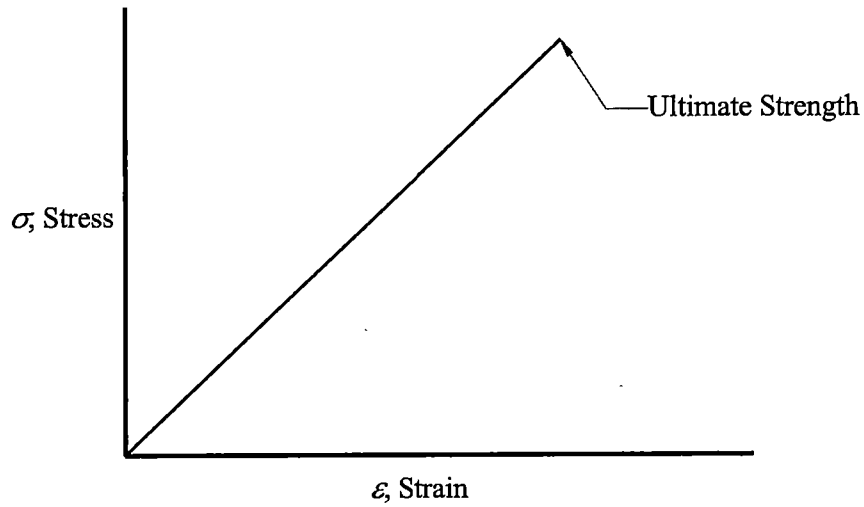


FIGURE 3.2
General stress-strain diagram for PVC

Table 3.1 Comparison of material properties for PVC and steel

	Polyvinyl Chloride	ASTM A36 Steel
Density	.048 lb/in^3	.283 lb/in^3
Modulus of Elasticity	411,000 psi	29 x 10^3 ksi
Poisson's Ratio	0.41	0.3
Coeff. of Thermal Expansion	2.9 x 10^{-5}	6.0 x 10^{-6}
Yield Strength	n/a	36 ksi
Ultimate Strength	7.5 ksi	n/a

Comparison of these values will aid in the correlation of results in the laboratory with results used in Finite Element Analysis (FEA). FEA is discussed in chapter 6.

CHAPTER 4

STRESS ANANLYSIS AND FAILURE CRITERION

4.1 Introduction

The main objective during the design phase was to determine what style of landing pad for a set area of steel plating could handle the highest amount of applied load when reaching its yield stress. As comparisons were made between the landing pad configurations and their stress behavior, it became easier to understand what characteristics decreased the stresses in a pad.

Determining the behavior of steel under load is complicated when dealing with uniquely shaped structures such as landing pads. When determining stress by mathematical analysis, it is customary to assume that the material in question is elastic, homogeneous, isotropic and infinitely divisible without change in properties. The interaction of multiple, independent stiffeners with a baseplate and center section creates a difficult structure to analyze.

Stress is not directly measurable – that is, it cannot be determined with one simple instrument. Thus, experimental determination of the stresses in a complex structural member, like that of a landing pad, requires measurement of the strain and subsequent calculation of the stress from Hooke's law.

4.2 Stress-Strain Relationship – Hooke's Law

A simple definition for strain is the ratio of length change to the original length of a body due to an applied load. In 1676 Robert Hooke, an English scientist,

set forth the relation that bears his name today. In essence, his statement for axially loaded members was that axial force and axial deformation are proportional. In most cases, engineering materials exhibit a linear relationship between stress and strain within the elastic region. This relationship can be expressed mathematically as

$$\sigma = E\varepsilon \tag{4.1}$$

where ε = *strain (in/in)*
E = *modulus of elasticity*

Assuming that Hooke's Law holds for the material of the pads under load, one can assume that load and deformation act proportionally. For instance, the bending of the baseplate or the compressive stress in the loading section will increase proportionally as the load is increased (Roarke, 1982).

Strain gages are commonly used in the laboratory to determine the strain in uniform material specimens. Measurement of strain is rather simple for the landing pads since the load applied to the body is uniform. Strain gages were used in conjunction with FEA analysis to determine stresses in the landing pads.

4.3 Calculating Stress in the Laboratory

For the landing pads discussed in Chapter 2, it was important to place the gages where the maximum stresses occurred. For this experiment, the main concern was the location of highest stresses in each pad. The location of the high stresses was necessary to help determine the placement of the strain gages. For this reason, stress analysis software was used to help determine areas of high stress and, in turn, where to place the strain gages. Figure 4.1 identifies the locations of the strain gages

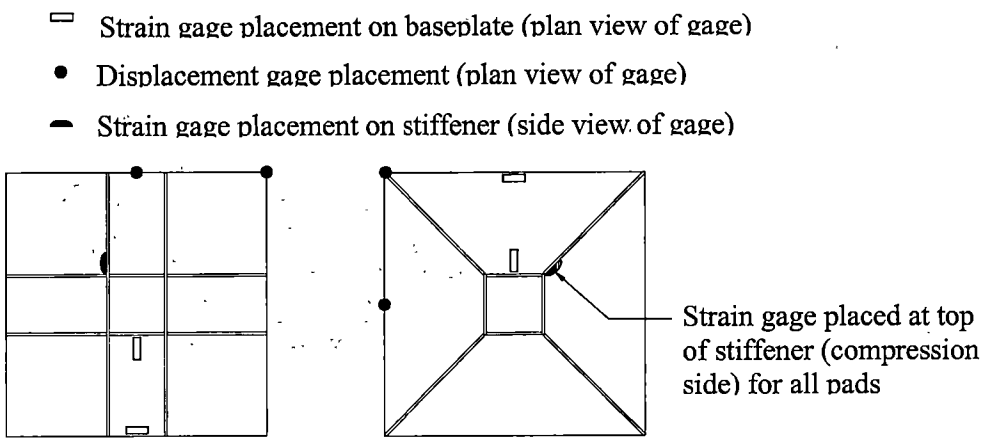


FIGURE 4.1
Placement of strain and dial gages for lab testing

on each of the two styles of landing pads. The figure also identifies the location of the displacement gages, which are discussed in the next chapter.

Strain gages determine strain by measuring changes in electrical resistance. The electrical resistance strain gage is a strain- sensitive component bonded to the surface of the model test part to measure its strain. When the strain gage is stretched (or compressed), its resistance changes in direct proportion to the strain because, as a wire is stretched, it increases in length, which in turn decreases in area. The change in cross-sectional area of the wire means an increase in the path of resistance.

Strain gages come in many different sizes and specifications. Most gages come with initial resistance values of 120 or 350 ohms. The most widely used and commercially available gages are 120 ohm gages like the one shown in Figure 4.2 were used for the laboratory experiments. The gage length or the active strain-

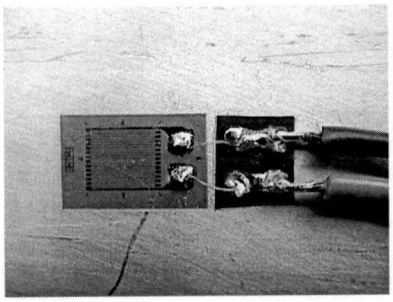


FIGURE 4.2
Photograph of a strain gage

sensitive portion of the gages used in these experiments was 0.5 inches. The strain gages were connected to the pads according to the recommendations of the gage manufacturer. After connection, all gages were checked with an ohmmeter to confirm the initial resistance.

The strain indicator or strain meter is the measurement device for the strain gages. The strain meter displays a value for strain in micro-inches by converting a supplied voltage to a new value for voltage according to the changes in resistance, or changes in the behavior of the strain gage. The strain indicator utilizes the concept of the Wheatstone Bridge. The Wheatstone Bridge is a simple circuit that allows the user to measure very subtle changes in resistance. After a strain reading was taken, it was multiplied by the modulus of elasticity to determine the corresponding stresses.

4.4 Possible Modes of Failure

It is difficult to predict how the landing pad will fail once it reaches a point of critical stress. If the landing pad is in fact a compressive member it could fail due to

compressive stresses, or even local buckling. This would be more likely in the case of a rigid subgrade. A baseplate would be more likely to fail due to bending stresses once loads are transferred from the loading section into the stiffeners. This would likely occur with a soft subgrade condition.

4.4.1 Compression

Compressive stress is important to understand in stress analysis for landing pads because the pad will be loaded in compression during laboratory testing and finite element analysis. The top of the landing pad will sustain a load equivalent to the weight of the equipment and stresses induced by wind. The bottom surface of the baseplate will undergo a soil bearing pressure equivalent to the load applied at the top of the pad.

Compression strength of a material is defined as the maximum load a material can support in compression without fracture. Since the landing pads were loaded statically in compression, it is possible that the pad could fail due to compressive stress or buckling of the plates in the center section of the pad directly below the loading device on the testing apparatus.

4.4.2 Bending Stress

The strength of some of the plates in the landing pads could be determined by the maximum bending moment they could sustain. This mode of failure would occur for landing pads loaded on very soft subgrades. The "softness" of the subgrade could allow for the baseplate to bend during loading. The failure in the baseplate due to bending would occur directly beneath the stiffener sections. As the bearing pressure

of the subgrade is increased, failure modes shift from bending stress in the baseplate to compressive stress in the center loading section. Orientation of the bending stresses would be perpendicular to orientation of the compressive stresses.

4.4.3 Local Buckling

The actual strength of the plate components for each of the landing pads could only be achieved if each plate element did not buckle locally. Local buckling will occur when the value for theoretical buckling stress in Equation 4.4 exceeds the yield stress in steel or the ultimate stress in PVC.

$$F_{cr} = k\frac{\pi^2 E}{12(1-\mu^2)(b/t)^2} \qquad (4.4)$$

where μ = *Poisson's ratio*
k = *buckling coefficient*
b = *base dimension (inches)*
t = *thickness of plate (inches)*

The value for k in Equation 4.4 is dependent upon the edge support conditions and length to width ratio (aspect ratio) of the plate (Salmon 1996). The buckling coefficient was determined using Figure 4.3, taken from the Salmon and Johnson text. For this investigation, the edges of the plate were considered simply supported perpendicular and parallel to the direction of loading. Tables 4.1 and 4.2 identify the theoretical buckling stresses for the steel and pvc plates at the loading section in the center of the pad. For this case, the steel pads in the loading section are stiffened elements since they were simply supported on both ends parallel to loading. No other plates in the pad were checked for local buckling since they were not directly loaded in compression. Note that all values exceeded 36 ksi so it was assumed that the steel

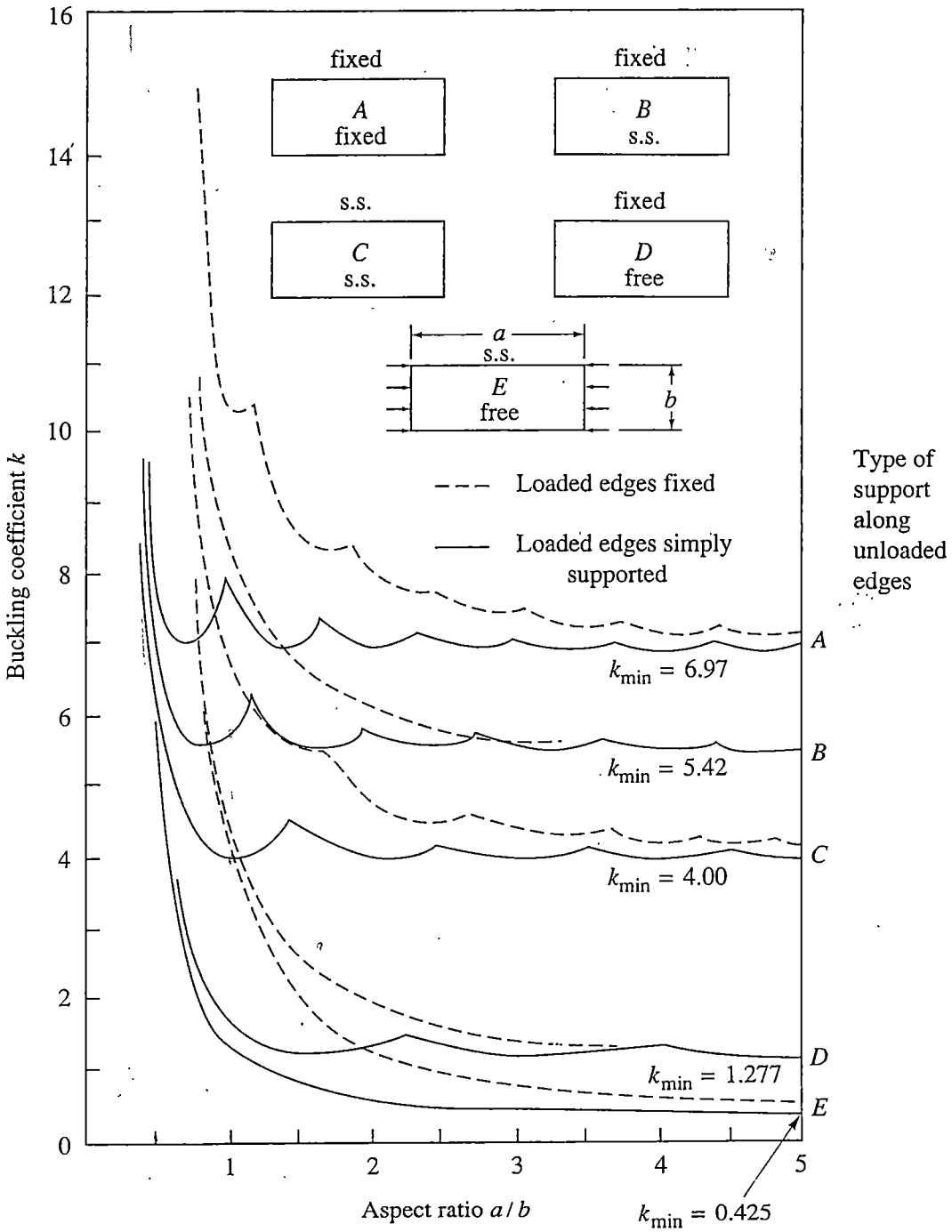


FIGURE 4.3
Elastic buckling coefficients for compression in flat rectangular plates (Salmon and Johnson)

Table 4.1 Values for theoretical buckling stress in steel pads

Pad	a/b (aspect ratio)	k	b/t	Fcr (ksi)
1	0.5	10	32	255
2	0.65	5	32	128
3	0.5	10	32	255
4	1	4	32	102

Table 4.2 Values for theoretical buckling stress in PVC pads

Pad	a/b (aspect ratio)	k	b/t	Fcr (ksi)
1	0.5	10	32	3.97
2	0.65	5	32	1.98
3	0.5	10	32	3.97
4	1	4	32	1.58

pads would not fail due to local buckling. Table 4.2 identifies the values for theoretical buckling stress in the PVC pads. All four of the pads' theoretical buckling stress fell below the value for ultimate stress.

CHAPTER 5
DEFLECTION

5.1 Introduction

It is difficult to determine the limits between reasonable and unreasonable deflection, especially for a unique structure such as a landing pad. When dealing with a beam or column, permissible deflection is typically dependent upon the span length. If the permissible deflection of a 30 ft span is 1 in, then it is usually no more objectionable than a deflection of only ½ inch in a 15 ft span. The American Institute of Steel Construction (AISC) Allowable Stress Design Manual (ASD) states that there is no single scale by which the limit of tolerable deflection can be defined. This statement also indicates that deflection limits must be decided on a case-by-case basis. The amount of deflection was considered during the optimization process of landing pad design. Maximum allowable deflection for the landing pads is a function of maximum vertical displacement versus the longest non-diagonal dimension. The longest non-diagonal dimension for all of the landing pads is along the outside edge and is equal to 18 inches.

5.2 Laboratory Testing of Displacement

In an effort to observe the displacement of the landing pads, laboratory testing was performed utilizing special equipment. The purpose of the laboratory experimentation was twofold: mainly, to give insight as to how landing pads behave when subjected to static loading, but also to provide a source that can be compared

with the deflection results obtained during FEA analysis. One of the more perplexing tasks was to predict how the landing pads would behave once they approach maximum allowable stresses for their constituent material.

Displacement in the laboratory was checked by the strategic placement of dial gages. The gages were placed at the midspan of the outer edge, and at the corners of all of the landing pads. According to the original FEA analysis and basic structural analysis techniques, these were the anticipated locations of highest displacement (see Chapter 6). A typical dial gage is shown in Figure 5.1.

Prior to testing, it was reasonable to assume that deflection values for the PVC models would be exaggerated compared to values for steel. Since steel models were not tested in the laboratory, it is important to understand the differences in the two materials in order to understand their behavior during FEA analysis. The value for

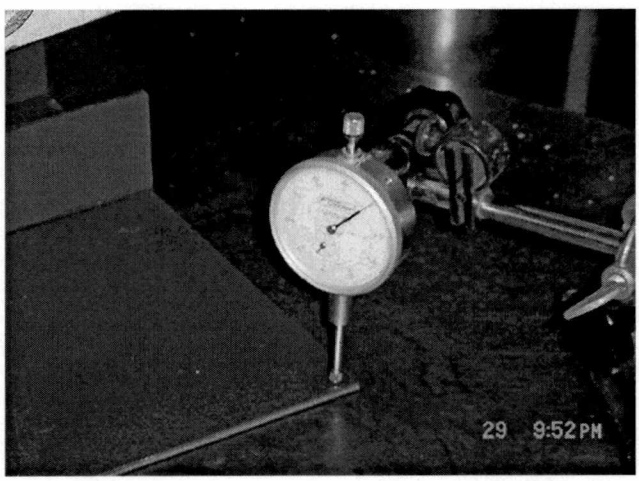


Figure 5.1
Dial gage for laboratory calculation of displacement

Modulus of Elasticity of the PVC used in the modeling procedures was 411,000 psi. This value was given by the technical data sheet supplied by the PVC manufacturer. The resistance to elastic behavior of the PVC is less than that of steel, and it is expected that deformation due to loading will occur in greater magnitude under the same load provided that the material does not fail before noticeable deflection.

The apparatus used for the compression testing in the laboratory was a Universal Testing machine. This machine is located in the Civil Engineering Laboratory of Estabrook Hall at The University of Tennessee, Knoxville. The apparatus was utilized to simulate loads applied to landing pads from portable equipment.

In an effort to simulate a real world scenario, the landing pads were placed on a steady, solid surface at the base of the testing apparatus in an effort to duplicate the rigidity of concrete and asphalt. These surfaces are the most common and are usually required by the manufacturer of the portable equipment. The top surface of the pad was covered with a 4-¼" x 4-¼" x ½" plate of aluminum. The section of aluminum was sized to fit the top surface of the pads, much like the compression member on machinery would do. The pads were then loaded continuously until they began to show signs of displacement. Maximum displacement readings were taken at the corresponding maximum allowable load value. These results are shown in Chapter 7.

CHAPTER 6

FINITE ELEMENT ANALYSIS (FEA)

6.1 Introduction

Finite Element Analysis (FEA) is a computer based, numerical technique for calculating the behavior and strength of structures. It can be used to calculate stress, deflection, vibration, and also buckling behavior.

In the finite element method, a structure is broken down into many small simple blocks called stress elements. The behavior of an individual element can be described with a relatively simple set of equations. Just as the set of elements would be joined together to build the whole structure, the equations describing the behaviors of the individual elements are joined into an extremely large set of equations that describe the behavior of the whole structure. The computer is used to solve this large set of simultaneous equations. From the solution, the computer extracts the behavior of the individual elements based on nodal displacements. From these displacements, it can determine the stress of all parts of the structure. The stresses are then compared to allowable stress values for the material to determine if the structure is of adequate strength.

6.2 How is Finite Element Analysis Useful?

FEA makes it possible to evaluate a detailed and complex structure, using a computer, during the planning of the structure. The demonstration by using computer solutions of the adequate strength of the structure and the possibility of improving the

design during planning can justify the cost of the analysis. FEA has also been known to increase the rating of structures that were significantly over-designed and built many decades ago.

In the absence of FEA (or other numerical analysis), strength performance of complicated structures was performed with more difficult and tedious methods such as 3D frame analysis and difficult hand calculations. For complex structures, such as landing pads, for instance, the simplifying assumptions required to make any calculations possible can lead to a conservative and heavy design. A considerable factor of ignorance can remain as to whether the structure would be adequate for all design loads. Significant changes in designs involve risk. Designs will require prototypes to be built and field-tested. The field test involves expensive strain gages and dial gages to evaluate strength and deformation.

With FEA, the weight of a design can be minimized, and there can be a reduction in the number of prototypes built. Field-testing should still be used to establish the maximum allowable load. FEA should then be used to do future design improvements.

6.3 Basic Principles of FEA

FEA allows the user to divide a complex structure into a simple grid of geometric shapes and connected elements. Displacement of element nodes are related to the simple equation

$$f = Kd \tag{6.1}$$

where f = vector of applied forces, K is the stiffness matrix and d = vector of node displacements. Based on the equations given and the results of node displacements, strain can be calculated along with the corresponding stress. Based on these general applications, stress can be calculated throughout the entire element.

The three basic steps for analyzing a model using FEA software are the following:

- Pre-processing: meshing, specifying boundary conditions
- Solution: solving using provided equations
- Post-processing: viewing and interpolating the results

The meshing process involves creating nodes and boundaries for important areas of intersection in the structure. During the input process, material properties such as modulus of elasticity must be specified. A meshing pattern may resemble that of Figure 6.1. It is important to simplify the geometry of the mesh such as using

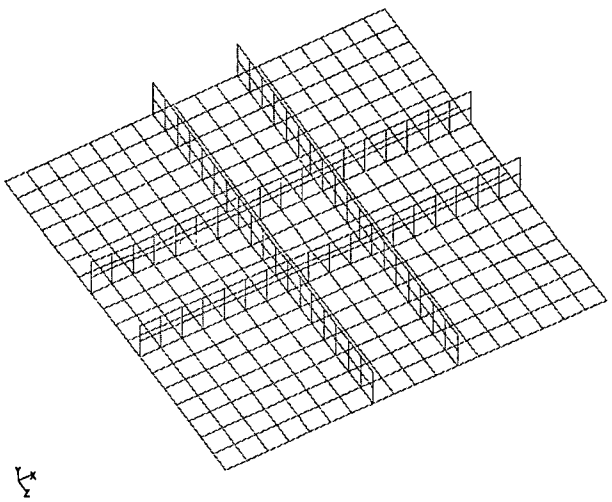


FIGURE 6.1
Example of meshing for Landing Pad 1

perpendicular lines and simple shapes, and by taking account of symmetry. Some software provides an automatic meshing option that will select geometric boundaries and placement of nodes on its own.

Once meshing is complete and boundary conditions are defined, the model can be solved. The computer can take minutes, hours, or even days depending on the complexity of the structure and the speed of the computer. Based on the theory of elasticity, stresses within the structure are determined by translating the strains in the object into stresses.

6.4 Boundary Conditions and Degrees of Freedom

During input of the model, degrees of freedom must be set for all nodes as well as the boundary conditions. For example: nodes at the fixed end of a cantilevered beam with a uniform load acting downward would have zero degrees of freedom. Nodes at the free end would have two degrees of freedom; one would be in the horizontal direction and the other would be in the vertical direction. Since there are no forces applied in the z-axis, there is no degree of freedom in this direction. Next the loads are applied to the nodes only in the matrix. For the landing pad models, all nodes comprising pad stiffeners and the loading section were given three degrees of freedom, or the ability to move in the x, y and z-axis. In some cases, the displacement of the nodes occurred in all three axes even though loading was performed in only one axis. Such displacements occurred in the stiffeners during loading in the softer subgrades; these values were very small compared to the

displacement values in the x and y-axis. All nodes encompassing the baseplate were supported by springs.

6.4.1 Spring Supports

Every node comprising the baseplate of each pad was supported with a spring. The springs were set at different stiffness values to represent varying subgrade conditions. Each 18 in x 18 in baseplate consisted of 324 square inch stress elements. For each of these stress elements, a spring support was attached at its four nodes. Each landing pad was loaded at each of the spring stiffness coefficients shown in Table 6.1.

6.4.2 Stress Elements

The basic building blocks of a Finite Element model are the stress elements, or elements, which make up the mesh. It is important to understand which type of elements to use for which type of structure for accurate results. Solid 3D regions, containing thin walled structures, have traditionally been meshed by using either 4-sided tetrahedral (TET) or 6-sided hexahedral (HEX) elements (Buchanan, 1995). These elements have the ability to let engineers determine stresses on any surface of

Table 6.1 Different values for k used in FEA analysis

Case	Spring Stiffness, k (lbs/in)	Scenario
1	2692.5	softest
2	15,000	medium
3	32,310	stiff
4	1,000,000	concrete

the model where maximum stress occurs. The size of the elements used is also an important issue. The smaller the stress elements used in the model, the more accurate the model will be. Caution must be taken so that an excessive number of stress elements are not used. Too many stress elements could tie up the computer and make final analysis tedious. Coming up with a reasonable size and quantity is part of the trick to good meshing (Buchanan, 1995). For ease of construction, the pads were constructed primarily of 1-inch x 1-inch stress elements (aspect ratio of one). In some cases elements had to be shortened in the y-axis, causing the aspect ratio to fall below one.

The types of stress elements used in STAAD/Pro© were HEX elements. The HEX element is traditionally an 8-node shape with six faces. See Figure 6.2 for an illustration of a HEX element. Constructing a HEX element in STAAD/Pro© requires only four nodes and the assignment of a thickness for each element in the shape modeler. The assignment of thickness creates a 3-dimensional stress element with the

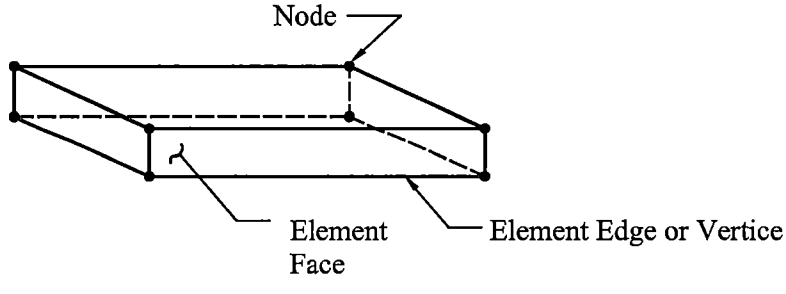


FIGURE 6.2
Diagram of traditional hexahedral (HEX) stress element

same amount of faces as a HEX element even though displacement is only identified for the four nodes. For sloped edges such as the triangular stiffeners in landing pad 2 and the parallelogram stiffeners in landing pad 4, some 3-node or triangular shaped stress elements were used. These stress elements were constructed with three nodes and the assignment of a thickness.

6.4.3 Loading Conditions

For the stress elements used, the FEA software allows two types of loading. The first is a pressure load or load distributed across the surface area of the element. The second is a point load allowing the user to place a load anywhere on the model surface. Both of these methods were utilized in the FEA analysis. The first loading condition called the "evenly distributed method" utilized an evenly distributed load across the entire surface area of the loading section. Figure 6.3 represents this technique.

The other loading technique utilized during modeling was the 4-point load technique. This method was used in order to pinpoint load to the intersection of the stiffener and loading sections in an attempt to increase stress performance of the pad.

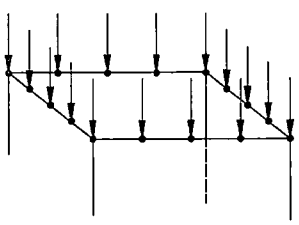


FIGURE 6.3
Diagram of evenly distributed loading technique

Figure 6.4 illustrates the principle of the 4-point loading technique.

6.5 Analysis with STAAD/PRO©

The models described in Chapter 2 were analyzed for stress with an FEA type software package called STAAD/Pro©. STAAD/Pro© is a popular structural analysis software with FEA capabilities. All four models were constructed in STAAD/Pro© and assigned material properties for A36 Carbon Steel with F_y = 36 ksi. The pads were then statically loaded until the point where maximum stresses reached the yield stress for steel and ultimate stress for PVC. Smaller load values were applied to determine more accurate values for failure.

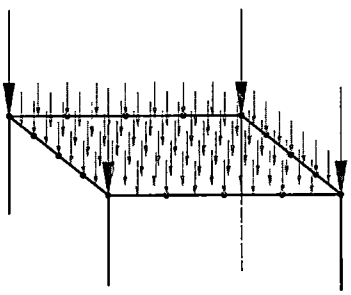


FIGURE 6.4
Diagram of 4-point loading technique

CHAPTER 7

ANALYTICAL AND EXPERIMENTAL RESULTS

7.1 STAAD/Pro© Results for Stress

Tables 7.1 and 7.2 identify the results obtained by loading the steel models in STAAD/Pro© for both the evenly distributed and 4-point loading conditions. The designated yield strength for the steel was set at 36 ksi. The shape and size of landing pads 1, 2, 3 and 4 in the following tables were constructed identical to the pads in Figure 2.2. For all subgrade cases, failure occurred due to compressive stress in the loading section. This was the result for both loading scenarios; however, failure due to compressive stress did migrate to the top inside edges of the stiffening sections with the 4-point loading method.

The PVC pads were analyzed for stress failure using two different failure criteria. Tables 7.3 and 7.4 represent the maximum allowable load in the PVC pads for both loading conditions when the model was set to fail due to a stress of 7.5 ksi.

Table 7.1 Maximum allowable load for steel pads modeled in STAAD/Pro© (evenly distributed load)

	Spring Stiffness, k		Maximum Allowable Load (lbs)			
Case	(lbs/in)	Scenario	LP 1	LP 2	LP 3	LP 4
1	2692.5	softest	17,562	14,637	13,712	15,319
2	15,000	medium	27,328	27,504	24,848	30,272
3	32,310	stiff	32,688	29,936	27,504	35,583
4	1,000,000	Concrete	34,212	31,245	28,549	37,446

Table 7.2 Maximum allowable load for steel pads modeled in STAAD/Pro© (4-point load)

Case	Spring Stiffness, k (lbs/in)	Scenario	Maximum Allowable Load (lbs) LP 1	LP 2	LP 3	LP 4
1	2692.5	softest	18,272	11,322	8,624	15,501
2	15,000	medium	24,232	16,400	15,408	22,224
3	32,310	stiff	28,620	20,512	22,304	25,248
4	1,000,000	Concrete	29,887	21,432	22,973	26,661

Table 7.3 Maximum allowable load for PVC pads with failure criterion at 7.5 ksi (evenly distributed load)

Pad	Max. Allowable Load (lbs)
1	15,028
2	14,398
3	14,927
4	15,112

Table 7.4 Maximum allowable load for PVC pads with failure criterion at 7.5 ksi (4-point load)

Pad	Max. Allowable Load (lbs)
1	11,667
2	8,002
3	8,921
4	9,132

Tables 7.5 and 7.6 represent the maximum allowable load in the PVC pads along with the associated limiting criterion value for local buckling for each loading condition. Since the loading section failed due to compression in these cases, it is accurate to speculate that PVC pads would actually fail at the values listed in Tables 7.5 and 7.6.

7.2 STAAD/Pro© Results for Deflection

For the evenly distributed loading method, maximum displacement locations for the steel pads occurred in two different places. For landing pad 1, the maximum displacement occurred on the baseplate beneath the centerline of the loading section. For landing pads 2, 3 and 4, the maximum displacement occurred at the top of the

Table 7.5 Maximum allowable load for PVC pads with failure criterion = F_{cr} (evenly distributed load)

Pad	Max. Allowable Load (lbs)	F_{cr} (ksi)
1	7,895	3.97
2	3,848	1.98
3	7,865	3.97
4	3,202	1.58

Table 7.6 Maximum allowable load for PVC pads with failure criterion = F_{cr} (4-point load)

Pad	Max. Allowable Load (lbs)	Fcr (ksi)
1	6,058	3.97
2	2,120	1.98
3	4,680	3.97
4	1,968	1.58

loading section stiffener centerline. Tables 7.7, 7.8 and 7.9 give the results for maximum displacement in the steel pads. Maximum displacement in the 4-point loading case occurred at the centerline and top of the vertical plates in the loading section. Tables 7.10 and 7.11 identify the values for maximum displacement and their location respectively.

Table 7.7 Maximum displacement in steel pads modeled in STAAD/Pro© (evenly distributed loading)

Case	Spring Stiffness, k (lbs/in)	Maximum Nodal Displacement (lbs) LP 1	LP 2	LP 3	LP 4
1	2692.5	0.046	0.047	0.050	0.043
2	15,000	0.025	0.030	0.028	0.028
3	32,310	0.019	0.020	0.020	0.021
4	1,000,000	0.017	0.018	0.019	0.018

Table 7.8 Maximum displacement location for landing pad 1

Case	Spring Stiffness, k (lbs/in)	Max. Displacement Location Landing Pad 1
1	2692.5	On baseplate beneath centerline of loading section
2	15,000	On baseplate beneath centerline of loading section
3	32,310	On baseplate beneath centerline of loading section
4	1,000,000	On baseplate beneath centerline of loading section

Table 7.9 Maximum displacement location for landing pads 2, 3 and 4

Case	Spring Stiffness, k (lbs/in)	Max. Displacement Location Landing Pads 2, 3 and 4
1	2692.5	Top of loading section stiffener at centerline
2	15,000	Top of loading section stiffener at centerline
3	32,310	Top of loading section stiffener at centerline
4	1,000,000	Top of loading section stiffener at centerline

Table 7.10 Maximum displacement in steel pads modeled in STAAD/Pro© (4-point loading)

Case	Spring Stiffness, k (lbs/in)	Maximum Nodal Displacement (lbs) LP 1	LP 2	LP 3	LP 4
1	2692.5	0.041	0.033	0.035	0.043
2	15,000	0.018	0.016	0.018	0.021
3	32,310	0.013	0.013	0.015	0.015
4	1,000,000	0.012	0.012	0.013	0.014

Table 7.11 Maximum displacement location for landing pads 1 through 4

Case	Spring Stiffness, k (lbs/in)	Max. Displacement Location Landing Pads 1, 2, 3 and 4
1	2692.5	Top of loading section at load location
2	15,000	Top of loading section at load location
3	32,310	Top of loading section at load location
4	1,000,000	Top of loading section at load location

Table 7.12 represents the values for maximum displacement as well as their locations in the PVC models for both loading scenarios. The closeness of the displacement values for landing pad 4 in both PVC and steel would suggest that the material under load was simply relieving itself during testing. That is, once the material slightly rose above the subsurface, it was no longer a load-carrying member of the pad. It appeared during testing that the outward edges of all of the pads rose during loading, indicating that they all behaved like cantilevers. This means that any elastic material would probably behave the same, regardless of the material's strength on an extremely rigid subgrade.

Table 7.12 Maximum displacement in PVC pads modeled in STAAD/Pro© at spring stiffness, k = 32,310 *lbs/in*

Landing Pad	Max. Deflection (in) (Evenly Distributed)	(4-Point)	Location
1	0.058	0.055	Top of Stiffener at centerline
2	0.066	0.065	Top of Stiffener at centerline
3	0.060	0.059	Top of Stiffener at centerline
4	0.022	0.020	Top of Stiffener at centerline

7.3 Laboratory Results

Laboratory testing for deflection and maximum allowable load was performed on the PVC pads at the campus of The University of Tennessee, Knoxville in Estabrook Hall. Figure 7.1 illustrates the setup of the testing apparatus and the stress analysis equipment during static testing. The tests were conducted over a span of 3 weeks and included all four PVC models. Displacement gages were strategically placed at the locations expected to produce the highest values. These areas were the midspan of the outside edges and at the far corners. Strain gages were placed in the three locations exhibiting the highest stress values. These locations were identified during primary FEA analysis with Ansys DesignSpace©.

Laboratory tests on the PVC pads with the universal testing machine revealed that the maximum stress values determined with the use of the STAAD/Pro© modeler were not similar. The ultimate loads obtained in the laboratory for landing pads 1 through 3 fell well below the FEA calculated values. Table 7.13 identifies maximum displacement results at ultimate strength for the PVC pads tested in the laboratory.

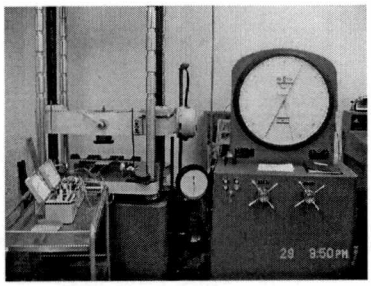
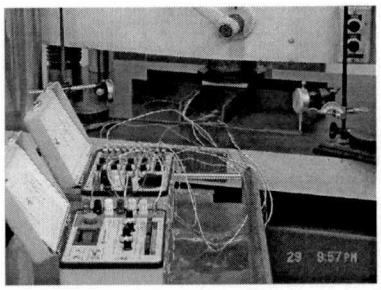



FIGURE 7.1
Universal testing apparatus used for laboratory experiments

If the limit state, L/360 specified in the ASD manual of steel construction is taken as the limiting criteria, landing pads 1 and 3 would not be acceptable. Deflection in landing pad 2 is equal to the limit specified, and considerations to decrease deflection should be made. Landing pad 4 met the requirements specified for this limit. Table 7.14 compares the values obtained in the FEA modeler for the PVC pads, to the values obtained during laboratory testing. The maximum displacement values shown in the table for the FEA analysis occurred at top of the loading section stiffener centerline. The maximum displacement in the laboratory was recorded on the outside edges of the pad. There was no room to record the maximum displacement in the laboratory at the center section since the dial gages would have interfered with the testing apparatus.

Tables 7.15 through 7.18 give values of stress and strain for the PVC pads tested in the laboratory. Strain readings were multiplied by the modulus of elasticity for PVC according to the requirements of Equation 4.1.

Table 7.13 Maximum values for displacement in PVC pads during laboratory testing at maximum allowable load

Landing Pad	Max. Displacement (in)	Location
1	0.181	Outside corners
2	0.050	Center span of outside edges
3	0.061	Center span of outside edges
4	0.036	Center span of outside edges

Table 7.14 Comparison of FEA and laboratory values for displacement in PVC pads

Landing Pad	Average FEA Results Max Displacement (in)	Lab Results Max Displacement (in)
1	0.057	0.181
2	0.066	0.050
3	0.060	0.061
4	0.021	0.036

The values for ultimate load, obtained during laboratory and FEA analysis, can be easily compared by looking at Table 7.19. The FEA results in Table 7.19 represent the average value for maximum allowable load for the two loading methods used. The failure criterion used in this table was the associated theoretical buckling stress identified in Chapter 4. The values obtained in the laboratory for landing pad 4 correlated the best with the values obtained in the FEA analysis.

Table 7.15 Stress-strain values for PVC landing pad 1

Load lbs.	Microstrains (in/in x 10^{-6})			Stress (psi)		
	Mid-span	Top of Stiffener	Inside Edge	Mid-span	Top of Stiffener	Inside Edge
0	0	0	0	0	0	0
100	2	212	175	1	87	72
200	5	480	365	2	197	150
300	7	712	561	3	293	231
400	11	958	712	5	394	293
500	14	1200	931	6	493	383
600	15	1485	1042	6	610	428
700	18	1710	1285	7	703	528
800	20	1975	1470	8	816	604
900	22	2220	1652	9	912	679
1000	24	2465	1893	10	1013	778
1100	26	2712	2022	11	1115	831
1200	28	2985	2237	12	1227	919
1300	31	3170	2460	13	1303	1011
1400	35	3440	2654	14	1414	1091
1500	38	3655	2838	16	1502	1166
1600	40	3998	3027	16	1643	1244
1700	43	4216	3121	18	1733	1283
1800	46	4480	3406	19	1841	1400
1900	49	4735	3585	20	1946	1473
2000	51	4985	3755	21	2049	1543
2200	57	5500	4137	23	2261	1700
2400	62	6002	4512	25	2467	1854
2600	65	6501	4912	27	2672	2019
2800	72	7001	5285	30	2877	2172
3000	77	7514	5689	32	3088	2338
3200	81	8001	6021	33	3288	2475
3400	88	8451	6420	36	3473	2639
3600	95	9001	6810	39	3699	2799
3680*	**98**	**9248**	**6985**	**40**	**3801**	**2871**

* Ultimate load strength of pad based on failure in the laboratory

Table 7.16 Stress-strain values for PVC landing pad 2

Load Lbs.	Microstrains (in/in x 10^{-6})			Stress (psi)		
	Mid-span	Top of Stiffener	Inside Edge	Mid-span	Top of Stiffener	Inside Edge
0	0	0	0	0	0	0
100	5	270	195	2	111	80
200	12	536	405	5	220	166
300	19	812	612	8	334	252
400	27	1110	840	11	456	345
500	33	1380	1035	14	567	425
600	40	1612	1250	16	663	514
700	47	1889	1445	19	776	594
800	55	2175	1685	23	894	693
900	60	2450	1897	25	1007	780
1000	70	2751	2102	29	1131	864
1100	74	2955	2314	30	1215	951
1200	82	3314	2312	34	1362	950
1300	91	3600	2741	37	1480	1127
1400	95	3836	2945	39	1577	1210
1500	100	4112	3140	41	1690	1291
1600	109	4412	3389	45	1813	1393
1700	118	4650	3630	48	1911	1492
1800	122	4955	3812	50	2037	1567
1900	130	5180	4020	53	2129	1652
2000	136	5492	4230	56	2257	1739
2080*	**141**	**5780**	**4421**	**58**	**2376**	**1817**

* Ultimate load strength of pad based on failure in the laboratory

Table 7.17 Stress-strain values for PVC landing pad 3

Load lbs.	Microstrains (in/in x 10^{-6})			Stress (psi)		
	Mid-span	Top of Stiffener	Inside Edge	Mid-span	Top of Stiffener	Inside Edge
0	0	0	0	0	0	0
100	6	221	205	2	91	84
200	14	458	412	6	188	169
300	22	701	620	9	288	255
400	31	1212	789	13	498	324
500	37	1408	1025	15	579	421
600	48	1655	1250	20	680	514
700	58	1941	1452	24	798	597
800	60	2180	1689	25	896	694
900	69	2420	1920	28	995	789
1000	77	2614	2014	32	1074	828
1100	86	2900	2210	35	1192	908
1200	94	2900	2540	39	1192	1044
1300	99	3105	2760	41	1276	1134
1400	108	3385	3045	44	1391	1251
1500	120	3560	3212	49	1463	1320
1600	122	3874	3485	50	1592	1432
1700	134	4120	3700	55	1693	1521
1800	140	4322	3912	58	1776	1608
1900	148	4606	4120	61	1893	1693
2000	156	4840	4345	64	1989	1786
2200	170	5318	4795	70	2186	1971
2400	185	5816	5011	76	2390	2060
2600	201	6303	5690	83	2591	2339
2800	219	6830	6120	90	2807	2515
2970*	**234**	**7137**	**6452**	**96**	**2933**	**2652**

* Ultimate load strength of pad based on failure in the laboratory

Table 7.18 Stress-strain values for PVC landing pad 4

Load lbs.	Microstrains (in/in x 10^{-6})			Stress (psi)		
	Mid-span	Top of Stiffener	Inside Edge	Mid-span	Top of Stiffener	Inside Edge
0	0	0	0	0	0	0
100	3	139	129	1	57	53
200	7	283	263	3	116	108
300	12	431	390	5	177	160
400	16	588	542	7	242	223
500	20	717	665	8	295	273
600	24	850	776	10	349	319
700	30	987	914	12	406	376
800	32	1149	1042	13	472	428
900	37	1288	1158	15	529	476
1000	43	1422	1308	18	584	538
1100	45	1575	1450	18	647	596
1200	48	1714	1580	20	704	649
1300	50	1845	1714	21	758	704
1400	51	2002	1840	21	823	756
1500	54	2100	1992	22	863	819
1600	60	2258	1970	25	928	810
1700	63	2363	2115	26	971	869
1800	66	2508	2400	27	1031	986
1900	71	2704	2530	29	1111	1040
2000	80	2856	2660	33	1174	1093
2200	88	3102	2906	36	1275	1194
2400	95	3358	3200	39	1380	1315
2600	108	3712	3452	44	1526	1419
2800	118	3980	3720	48	1636	1529
3000	125	4320	4000	51	1776	1644
3200	130	4590	4260	53	1886	1751
3400	140	4857	4660	58	1996	1915
3600	151	5161	4792	62	2121	1970
3800	158	5470	5080	65	2248	2088
4000	165	5755	5341	68	2365	2195
4180*	**180**	**5989**	**5488**	**74**	**2461**	**2256**

* Ultimate load strength of pad based on failure in the laboratory

Table 7.19 Comparison of ultimate load values for PVC pads

Landing Pad	FEA Results* Ultimate Load (lbs)	Laboratory Results Ultimate Load (lbs)	Difference (lbs)	Lab Results / FEA Results
1	6977	3680	3297	0.527
2	2984	2080	904	0.697
3	6273	2970	3303	0.473
4	2585	4180	(1595)	1.62

* FEA results for ultimate load are the average for both the evenly distributed and 4-point loading methods

CHAPTER 8

CONCLUSIONS

8.1 Introduction

The general design of a landing pad is dependent upon its application. There are many factors other than stress and displacement that could affect the design. Some clients may desire larger pads to eliminate failure risks when cost is not a concern. Some clients may require a covered pad to eliminate the trapping of rain and soil to keep the pads aesthetically pleasing.

8.2 Design Suggestions and Conclusions

According to the stress performance results obtained during laboratory and FEA analysis, landing pads 1 and 4 perform the best for the subgrade conditions used in this experimentation. Landing pad 1 performed the best for the 4-point loading method and landing pad 4 performed the best for the evenly distributed method.

PVC does behave similar to steel in the elastic region of the stress and strain curve; however, it is not a good material to use for laboratory analysis. PVC plates comprising the loading section are more likely to buckle in the case of the dimensions used in this analysis. If PVC had to be used as a testing material, it would be better to provide a thickness or dimension of PVC that would prevent local buckling. This would allow the material to fail because of critical stress and would give results that could be effectively compared to maximum allowable load values in steel

Excluding landing pad 4, the laboratory values for maximum allowable load in the PVC pads were well below the FEA analysis values; this was true even in the case where local buckling was the limiting design criteria. The poor showing in the laboratory can be attributed to imperfect construction and a bonding agent with an ultimate strength less than that of the PVC. Better results could have been achieved if steel had been used and the components of the pad had been professionally welded. Initially FEA analysis was performed with improper boundary conditions. Because strain gages were positioned on the pad in the areas determined by the original FEA analysis, strain gage placement was never pinpointed on the areas of highest stress. The size and shape of the pads also made it difficult to place the strain gages in some of these areas.

FEA analysis revealed that maximum displacement occurred at the loading section or center of the pad for the all of the subgrade conditions. Due to equipment interference, displacement gages could not be placed in this location during laboratory testing of the pads. Because of this, actual maximum displacement measurements could have never been measured for the PVC pads using dial gages.

Based on the results of the stress analysis, it was concluded that stress levels in a landing pad migrate to the center of the pad as the rigidity of the subgrade is increased. All subgrade conditions used in this experimentation failed due to compressive stresses or local buckling in the center section. If an extremely soft subgrade condition were tested, the maximum stress levels would occur in the

baseplate and follow the pattern of the stiffeners. With this in mind a landing pad should be designed according to the following guidelines:

- For all rigid subgrade conditions thickness of the loading section is important. Increase the thickness of the vertical plates in the loading section to compensate for compressive stresses. It is also important to keep the height of the plates in the loading section to a minimum. Thickness of the plates in the loading section as well as height of the plates both contribute to the condition at which the plates will locally buckle. It is first and foremost important to design a loading section that will not locally buckle.
- Addition of extra stiffeners is always a good idea for increasing strength. Also, increasing the thickness of the material used is good for increasing strength. One should keep in mind that adding more material increases weight, which limits the ease of handling. It is up to the user on a case-by-case basis to decide what parameters are most important.
- The 4-point loading method used in this analysis did concentrate more load to the stiffeners; however, it ultimately reduced the overall strength of the pad. The compression member should be designed and connected to evenly distribute the load across the entire surface area of the loading section.
- Increase the depth of the stiffener as it approaches the center of the pad to accommodate increases in bending stress. A triangular pattern should be utilized with the smaller height beginning on the outside edge and the larger height at the center of the pad.
- Small amounts of stiffener on the outside edges of the pad tend to affect displacement in a positive way when maximum displacement is on the outside edges of the pad. If the elimination of displacement in

extremely high load cases is a concern, material can be added to the outside edges of the pad to reduce displacement. The displacement values observed in the laboratory were extremely small and would not be evident to the naked eye, however. For this reason displacement was not used as a design criteria.

- The number of portable foundations should be based on a simple formula: increase the number of landing pads for equipment based on the loading capacity. A good rule of thumb is to provide enough pads to adequately support 1.2 times the dead load and 1.6 times the maximum live load of the equipment.

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