COMPREHENSIVE COMPARISON OF STEEL FRAMED FABRIC AND CONVENTIONALLY CONSTRUCTED AIRCRAFT HANGARS

THESIS

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Abstract

Through the life of the United States Air Force (USAF), the accepted method for constructing permanent aircraft hangars is the use of materials such as steel and concrete. However, the emerging type of construction known as steel framed fabric (SFF) construction shows potential to meet the requirements of the USAF at a lower life-cycle cost and with faster construction delivery. A comprehensive comparison to conventional hangars is conducted through the means of an extensive literature review, case study analysis, structural analysis with the use of finite element analysis (FEA) software, and a life-cycle cost comparison. Through examination of Department of Defense (DoD) Unified Facility Criteria, industry building codes, and best practices, there are no significant barriers keeping the USAF/DoD from constructing SFF hangars. The FEA of a simplified SFF model reinforced that fabric membranes can provide equal, if not more, structural safety in comparison to conventional hangar claddings. This research recommends the USAF implement SFF hangars as an alternative to conventional construction for new aircraft hangar projects. By investing in SFF, the USAF will save considerable costs to the US taxpayer. Shorter construction delivery times will allow commanders more flexibility in mission bed-down. Lastly, reduced maintenance concerns typical of SFF hangars will lessen the burden on facility maintenance personnel.

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Capt Justin Iungerich

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COMPREHENSIVE COMPARISON OF STEEL FRAMED FABRIC AND CONVENTIONALLY CONSTRUCTED AIRCRAFT HANGARS

I. Introduction

General Issue

Through the life of the United States Air Force (USAF) the accepted and typical method for constructing aircraft hangars is the use of tried and true materials such as steel and concrete. More specifically, most aircraft hangars have primary load bearing walls and framing constructed of steel and reinforced concrete and use a form of steel cladding for roof material. Given the constrained budget for military construction (MILCON), the USAF has had to begin to explore alternative constructions methods other than conventional construction. Conventional steel, masonry, wood, and reinforced concrete construction has a long record of producing facilities that have service lives exceeding 25 years, the military standard for service lives of permanently constructed facilities, and therefore the USAF has had little reason to research alternatives (Defense). However, an emerging type of construction is steel framed fabric construction, which shows potential to meet the needs of the USAF at a lower life-cycle cost. Steel framed fabric construction, which is a method of fabric construction, uses engineered fabric as cladding that is stretched over top the structure's steel frame. The primary distinction between fabric and conventional is the structure's cladding. This difference imposes many other distinguishing factors between the two types of construction such as structural capabilities and limits on facility function. This research will examine these differences between construction methods for the specific application to permanent USAF aircraft hangars.

Currently, across the United States Air Force (USAF) facility inventory, there exists but one aircraft hangar at Tinker Air Force Base, Oklahoma, permanently constructed using the steel framed fabric construction method (Air Force Civil Engineer Center). In comparison, private industry and public airports have a long history of investment in steel framed fabric. Use of tensile fabric construction for long span structures such as stadiums, large storage facilities, maintenance warehouses, and factories began in 1909 with the construction of a zeppelin hangar in Frankfurt, Germany (Wilkinson). However, beyond the functional use for large span airship hangars in the world war era, the use of fabric as major construction material did not gain popularity until innovative designers such as Frei Otto and Horst Berger, started to showcase the material's potential at large public conventions in the 1960s and '70s (R. Shaeffer). From that time, an entire fabric construction industry has blossomed as engineers and architects have realized the vast and growing applications of engineered fabrics as a building material. Today, there are examples of commercial airlines and public airports using steel framed fabric for permanent hangar construction such as the Southwest Airlines Maintenance Hangar at Jackson-Hartfield Atlanta International Airport (New South Construction), and the AAR Inc. Maintenance, Repair, and Overhaul (MRO) Hangar at Rockford International Airport (Rubb Building Systems).

There are distinct implications for construction projects and built facilities on AFBs as opposed to work done outside of the DoD. First and foremost among these differences, is the fact that USAF construction and design requirements are driven by the war-fighting mission and the various aircraft and personnel specialties that are housed within facilities. In most cases there are higher hazards such as explosives and sensitive combustible fluids contained within facilities. As a visible symbol of our nation's military might, USAF facilities have an inherent risk as a target for our nation's enemies, and therefore commanders mitigate against that risk by going above and beyond the requirements of the International Building Code (IBC). These exceptions are outlined in the DoD's Unified Facility Criteria (UFC) which is the DoD building code. In addition, like many other government entities, the DoD builds its construction standards with the weight of responsibility to tax payer dollars such that projects are cost effective over the life cycle of the facility (Department of Defense). This research is justified and necessary for the USAF because it will distinguish itself by focusing on the differences imposed by DoD standards on fabric construction as opposed to the proven application in private industry.

Within the past decade the USAF and the DoD have begun to implement fabric construction in temporary structures such as sun-shades and relocatable Large Area Maintenance Shelters (LAMS). Temporary structures as defined by UFC 1-200-01 are "buildings and facilities designed and constructed to serve a life expectancy of five years or less using low cost construction." The flexibility of this construction method and its speedy construction time have sold the USAF and DoD on its practicality as a deployable expeditionary construction method. The USAF has established standardized deployable kits for temporary structures that many Airmen in the Civil Engineering career field are trained to construct. Therefore, it is apparent that the USAF and DoD are convinced of the capabilities of fabric construction as it is applied to temporary facilities. However, given that the USAF has only the one test case at Tinker AFB of a permanently constructed tensile fabric hangar, there is not much data within the USAF and DoD on which USAF leaders can base a decision to continue investing in this method for permanent construction. Additionally, with the current restrained budget for military construction (MILCON) projects, it is very difficult for an organization such as the USAF to commit to fabric construction as it has with conventional methods such as steel, concrete, masonry, and wood when it is unclear how the new type of facility will standup to USAF requirements in the future.

The USAF has already established that fabric construction is effective in contingency environments where temporary and mobile facilities are a necessity. As stated above, the intent for temporary construction is for the facility to be designed for up to a five-year useful life. In reality many of the structures, such as the hangar facilities manufactured by Alaska Structures Inc., that the USAF and DoD use in deployed locations, are in use for longer than twenty years. The recent up-tick of private sector and government agencies making use of fabric construction for permanent aircraft hangars, has sparked USAF interest in situations where fabric makes more sense than conventional construction. In order to meet USAF and Federal mandates to seek out economical and sustainable construction methods that minimize ownership costs while meeting mission requirements, a holistic investigation of how fabric construction compares to conventional construction is required (Department of Defense).

Problem Statement

Currently, the USAF does not have the historical data and established service standards to support recommendations for the use of steel framed fabric construction for permanent aircraft hangars. As stated earlier, the sole data point for USAF permanently constructed tensile fabric hangars is the Maintenance Repair Overhaul Technology Center (MROTC) hangar attached to Tinker AFB. As for existing DoD design and construction standards, which are primarily comprised by the Unified Facility Criteria (UFC), UFC 4-211-01, titled *Aircraft Maintenance Hangars*, contains the following guidance on tensile fabric aircraft hangars:

> Group IV hangars as defined by NFPA 409 (tension fabric structures on metal structural frames) are permitted when sited and constructed in accordance with this UFC specific to Group IV hangars. Where Group IV hangars are provided, protect them in accordance with the requirements of this UFC, including overhead sprinkler protection, Hi-Ex foam, fire alarm and mass notification, and hangar bay egress. (Sec. 5-6.1.2)

Sec 7-6.2 continues to elaborate on National Fire Protection Association (NFPA) 409 driven requirements. When compared to the rest of that 288-page UFC which specifies design and construction guidance for steel and reinforced concrete construction methods, other than the paragraph shown above there is no guidance for the tensile fabric construction method that permits its use. In order to provide guidance on this type of construction and fill voids in the UFC, AFCEC and the functional agencies from other service branches require research into what exists in industry building codes, standards, and accepted best practices. The industry guidance must then be compiled by Naval Facilities Engineering Command (NAVFAC), US Army Corps of Engineers (USACE), and AFCEC and catered to meet the needs of each service branch to be published in the UFC.

One of the drivers for this research is the knowledge gap often found by AFCEC staff members when communicating with USAF project managers who are in charge of projects associated with fabric construction. As will be discussed in the case study narrative, this sentiment was a common theme among interviewed AFCEC staff members that worry that USAF project managers whether, civilian or military, are not equipped with guidance on how to review design of fabric clad structures. It must be understood that tensile fabric does not behave linearly like steel and concrete in reaction to loading. The design from a manufacturer, or specialty contractor, must show that this complex behavior is accounted for (C. G. Huntington). The guidance provided and distilled from literature in this research does not aim to teach USAF project managers conceptual understanding of the structural behavior of fabric, but to simply equip them with guidance that will ensure they can properly manage and review these type of projects.

AFCEC staff members have conducted a cursory survey into viable methods of incorporating fabric technology into USAF permanent construction projects (Air Force Civil Engineer Center). This research discovered that the USAF needs a more rigorous exploration into the capabilities of fabric construction to inform a decision on whether or not to invest in the new type of construction. In order to support future decisions, it must be shown that when compared to conventional construction methods, fabric construction can provide equivalent or greater structural safety, can support the same functions required by USAF aircraft mission sets, and over an equal lifespan, has an equivalent or lower cost to the taxpayer to construct, maintain and operate. Equally as significant, is whether or not tensile fabric aircraft hangars are practical for the permanent use of USAF mission sets. Therefore, there are four decision criteria that form the framework of what will be investigated in this research: research consensus, structural safety, mission functionality, and economic feasibility.

Research Objectives/Questions/Hypotheses

The first objective of this research project, coinciding with the criterion of research consensus, is to provide guidance about tensile fabric structures that can be implemented by the DoD in writing construction and design standards such as UFCs. The use of fabric construction by the DoD is contingent upon whether it meets or exceeds the performance of conventional methods. Therefore, this research will also discuss the comparison of fabric to conventional construction as presented in current literature. In addition to providing construction and design guidance, this research will also recommend feasible options for fabric materials that meet the needs of USAF permanent construction and are readily available on the construction market. This combined narrative will look comprehensively at design, construction, and maintenance of aircraft hangars as an outline for how to structure guidance for the unique case of tensile fabric construction.

Next, the research will draw from the experience of those closest to the tensile fabric construction industry, leading USAF aircraft hangar construction and design experts, operators and maintainers of existing fabric facilities, and architectural fabric manufacturers to explore mission functionality of this new type of construction. By gaining first and third-person accounts of how these facilities function the research will illuminate the realities of fabric construction and answer the question of whether or not is practical for the USAF. Practicality in this context is taken to be independent of whether or not the construction method meets DoD construction and design standards since that question will be answered in the previous section of research. This section will also discuss how fabric construction will change the way USAF project managers and facility management personnel perform their duties. In addition to questions regarding practicality, the case study process askes many of the same questions that were addressed in the previous general comparison section in order to reinforce or reject the prevailing literature narrative through first-hand experience.

The third primary criterion of whether the USAF chooses to use tensile fabric construction is whether or not it is as structurally safe as conventional construction. To make this comparison, a simplified model of a KC-46 (the USAF's new cargo fuel tanker aircraft) hangar will be created using Abaqus CAE © finite element modeling software with cladding of both fabric and conventional construction. These two models will then undergo equivalent loading conditions associated with environmental conditions and UFC requirements for the location of Tinker AFB, Oklahoma. Ultimately, factors of safety will be calculated for each model based on controlling loading conditions and the capacities of fabric and conventional construction cladding to be compared. The results of this comparison will speak to structural capabilities for fabric clad aircraft hangars in a large swath of the central U.S., and may serve as a benchmark for further research at different locations and facility sizes.

Finally, the question of whether tensile fabric hangars are more economically beneficial decision over the life cycle of the facility than conventional hangars. As stewards of US taxpayer dollars, life cycle cost effectiveness must always be considered when planning construction projects. Air Force Instruction (AFI) 32-1032, the USAF's guiding document on planning and programming repair, and maintenance and construction projects, requires Base Civil Engineers (BCEs) to "… determine solutions to: … provide, … facilities, infrastructure, and installations for effective mission support at the lowest life-cycle cost…" (United States Air Force). Using the guidance laid out in UFC 1-200-02 *High Performance and Sustainable Building Requirements*, the life-cycle cost analysis (LCCA) will be assessed at a lifetime of 40 years. This 40 year requirement differs from the previously mentioned 25 years since the guidance on LCCAs does not prescribe facility service life; it simply specifies DoD guidance on how to perform LCCA on a facility. The LCCA will use the same KC-46 hangar as the structural comparison for comparing initial design and construction costs, maintenance and repair, and operating costs of the two types of construction. Cost data will be garnered from DoD facility records, industry construction and maintenance data, and cost data published in literature. It is the predicted that fabric construction will be equivalent to, or more cost effective than conventional construction.

Research Focus

There are many ways in which fabric construction can be used on large span structures to create unique designs and captivating works of architecture. This research will not explore the more complex forms commonly implemented in structures such as sports stadia and performance arenas. The structure of concern is an aircraft hangar with tensioned fabric cladding on a steel frame skeleton. Large bay maintenance hangars are of interest so the approximate size of the facility is 200 feet by 200 feet.

The location of structural and cost analyses will be limited to Tinker AFB. This limits what can be said about the rest of the AFBs throughout the U.S and overseas. However, throughout the literature review and discussion of general guidance, the location will not be controlled, so the research will be applicable, to varying degrees, to all locations.

A current gap in this research that is unique to the DoD is the analysis of how this type of construction resists the impact loading of an explosion as is done with all other common used types of construction on USAF installations. This will be explored in the literature and case study interviews to discern if there are obvious concerns with using this construction in instances with high levels of risk associated with ordinance explosion. The structural analysis will not account for impact loading from an explosion.

Methodology

The research will implement several methodologies to analyze the many areas of interest when it comes to building a permanent tensile fabric aircraft hangar on a USAF installation. Initially, to provide guidance to USAF standard writers, a comprehensive literature review of existing industry standards and practices will be conducted. The literature review will also provide recommendations for material selection that aligns with the requirements for permanent construction. Lastly, the literature review will also be used to form a narrative comparing tensile fabric construction to current USAF accepted construction methods.

In order to build a narrative based on first-hand accounts of experience with design, construction, maintenance, and operation of tensile fabric aircraft hangars, an instrumental case study as defined by Maggi Savin-Baden in *Qualitative Research* will be conducted (Qualitative Research, Ch 23). In general, this method involves conducting loosely structured interviews with subjects using questions that are catered towards the subjects' specific experience and relevance towards the research topic. In the case of fabric construction, interviews will be conducted with hangar facility managers to gain insight into operations and maintenance, contractors with construction and maintenance experience involving fabric clad hangars, USAF staff members who have researched and managed aircraft hangar construction projects, and relevant manufacturers that feed the fabric construction industry.

The structural analysis portion of this research project involves comparing two equivalent computer-based models of the conventional and fabric construction methods. This analysis will be performed with the aid of finite element analysis software and design load calculations will follow guidance relevant to each type of construction as specified in the IBC. The design for the model will be a simplified version of a recently completed design for a steel and masonry clad KC-46 hangar to be constructed at Tinker AFB.

Lastly, a LCCA will be performed for both a conventionally constructed and a tensile fabric hangar of equal size, location, and function to analyze the economic feasibility of the USAF constructing and maintaining tensile fabric aircraft hangars.

Assumptions/Limitations

Key assumptions must be made to limit this research in scope while still providing scientifically meaningful results. In the development of this research project the following assumptions were made: The location for structural analysis of Tinker AFB will be useful in providing a baseline for studying how the structural capabilities of tensile fabric hangars compare to that of conventional. The structural analysis will only compare differences in cladding between conventional steel and fabric hangars. The supporting superstructure will remain the same for both models. It is also assumed that the chosen location will provide a meaningful economic comparison. The use of a case study for qualitative analysis also limits what can be said about the topic. However, the goal is not for the case study to provide general guidance, but to highlight specific anecdotes of where themes shown in the literature can either be realized or corrected. Since this topic is fairly new to the USAF, and even the AFCEC aircraft hangar construction experts that were interviewed, it is worth acknowledging that their capacity to speak on all aspects of fabric construction is limited. However, it is also assumed that the audience is familiar with general concepts of hangar design. This reinforces the decision to use the case study analysis, which allows the flexibility to steer interviews of each subject towards questions that emphasize their individual experience and expertise on the matter.

Implications

The goal of this research project is to provide a comprehensive impartial analysis to AFCEC, so that strategic decisions can be made for the future of construction methods used on MILCON projects. This includes assisting the DoD in writing guidance for construction and maintenance of permanent tensile fabric hangars. As this is the first step the USAF has taken to research this topic and gather data on this type of construction. It will be a stepping stone for future research.

Outline of Chapters

The structure of this paper will be arranged similarly to the order of discussion that was used in this introductory section. Beginning with the next chapter, the literature review will build a base of knowledge that is distilled from prevailing texts that are relevant to design, construction, maintenance and operation of tensile fabric structures. In addition, a large portion of literature research will be dedicated to aircraft hangar and large-span structure construction in order to provide a base of knowledge with which to compare fabric construction. Following the literature review, the methodology will provide a detailed explanation of the four types of analysis planned for this project as discussed above. The last portion of this paper will then be dedicated to the results of each analysis and conclusions that can be drawn from the completed work.

II. Literature Review

Chapter Overview

This chapter will synthesize prevailing trends from leading research and literature on the design, construction and maintenance of tensile fabric aircraft hangars, fabric material selection for permanent construction, and present a narrative that compares tensile fabric construction and current USAF accepted construction methods. This begins with an introduction of the concept of tensile fabric as a major construction material, followed by the history of its development from a conceptual breakthrough to the utility it sees today in the private construction industry. Next, the key concepts relevant to the design of fabric structures will be discussed in the framework of DoD design requirements. This will include a similar discussion of conventional design. However, with less of a focus on introducing ideas since it is assumed that the reader will be familiar with much of the conventional design concepts. A comparison will then be made between construction of an aircraft hangar using conventional and tensile fabric methods, providing advantages and limitations for both methods. The last comparative section will discuss the maintenance of both types of construction over the facility's service life. The chapter will conclude with a survey of recent research in the fabric construction industry to support later recommendations for the USAF on the selection of a type of fabric that will meet the needs of permanent aircraft hangars.

Brief History and Description of Fabric Structures

Recounting the history of how tensile fabric technology has been used in the past will provide an understanding of how the technology could potentially be implemented by the DoD for use in current and future permanent aircraft hangars. This includes lessons to be gained from the successes and missteps of the industry. In addition, a portion of this section will be dedicated to developing an intuitive concept of what tensile fabric construction is, and its governing physical characteristics.

In the introduction of this paper an expedient definition and description of tensile fabric construction was given simply as an engineered fabric stretched over a steel structural frame. A more refined definition for subsequent use throughout this paper is necessary. As defined by C.G. Huntington, a leading researcher and practicing structural engineer in the field of fabric construction, "tensioned fabric structures are covers or enclosures in which fabric is pre-shaped and pretensioned to provide a shape that is stable under environmental loads (C. G. Huntington)." At this point, establishing a general understanding of how fabric resists loading, the basic composition of structural fabrics, and general design approach shall be sufficient.

As introduced in a recent round robin analysis exercise that combined the expertise of several prominent universities and engineering firms, a key concept to understanding the design of fabric structures is that fabric, as a construction material, has negligible ability to resist bending and compression forces as conventional materials do.

This requires that fabric structures be designed with sufficient curvature to enable the fabric to resist forces in tension and shear in the plane of the fabric. This is the case when tensile fabric is used as a primary structural support of the building. In the case of aircraft hangars, this research is concerned with fabric as a non-structural cladding, and therefore the curvature of the fabric is not as crucial to the performance of the structure (P.D. Gosling a). Another key to ensuring that fabric is acting in tension is that the fabric is prestressed sufficiently that it maintains its form in any load conditions (P.D. Gosling a). ASCE 55, the governing design code for tensile membrane structures, emphasizes that in the case of fabric as cladding, prestressing is crucial since this will keep the fabric from going slack in certain areas which results in eventual tears of the fabric (American Society of Civil Engineers).

The composition of tensile fabrics, like most conventional materials, has a significant influence on how the material performs as a part of a building and what approaches must be taken in the design process. Fabrics are woven materials in which small perpendicularly oriented bundles of fibers (known as yarns) are interwoven to make up tensile load bearing "scrim" upon which protective coating is applied that protects the scrim from weather and ultra-violet (UV) deterioration, provides fire resistance, and provides the ability to resist in-plane shear loading (C. G. Huntington). Figure 1 below provides an intuitive depiction of the main components in a tensile fabric.

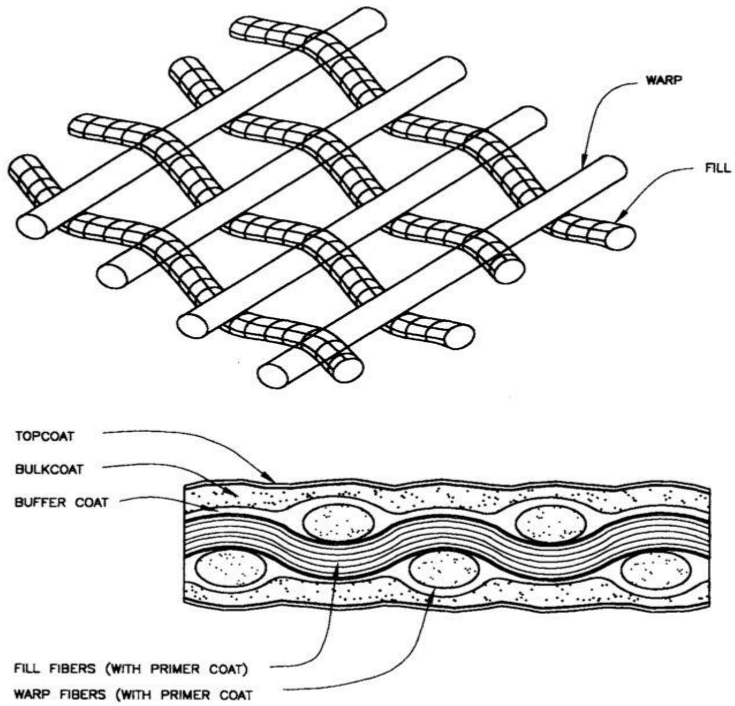


Figure 1. Top image shows scrim with woven yarns of the warp and fill directions. Bottom image shows a typical cross section of a tensile fabric with the arrangement of coatings and scrim **(C. G. Huntington)**.

The Task Committee on Tensioned Fabric Structures produced a report in 2013 with the intent of providing an introduction to the concept of tensioned fabric structures. In the report, the naming convention for the yarn directions identifies the initial direction that is laid straight in the weave as the warp direction, and the direction that passes around the warp yarn, as the fill or weft direction. The different coatings shown in the bottom image of Figure 1 can provide varying benefits to the membrane such as ultra violet (UV) protection, self-cleaning, added durability, and flame resistance (Task Committee on Tensioned Fabric Structures).

Due to the above characteristics and others, fabric structures behave in a highly nonlinear fashion in response to loading and therefore require a more complex and involved design from engineers. Nonlinearity is desirable because tensile fabric structures increase load carrying capacity as they deform over time (Task Committee on Tensioned Fabric Structures). In the structural analysis and design text, *Structures,* by Schodeck and Bechtold, the nonlinear behavior is described as being comparable to the phenomena seen in steel members. Once the steel member is loaded past its yield strength and proceeds to behave in a nonlinear plastic fashion, it gains load bearing capacity in the process, known as strain hardening (D. Schodek). As is explained in the conference paper published by tensile fabric consultants Houtman and Orpana, fabrics behave differently due to the weaving process and the interaction of the orthogonal yarns. Conventional construction largely uses materials that are isotropic. These materials will respond to loading similarly for all orientations of the loaded member, all other things equal. Materials used in tensile fabric construction are characterized by anisotropy. Due to the bidirectional weave, the strength of the fabric will differ depending on the direction in which load is applied (R. Houtman).

In addition to these general concepts, it is important to also understand the history and development of the fabric construction industry. Seaman Corporation, a leading manufacturer of engineered fabrics, has the following to say about the history of fabric construction: “Fabric structures in the form of tents have been around for thousands of years, but it is only within the last fifty years that the design and construction of tensile membrane structures have begun to surface as a viable, permanent building method” (Bradenburg, Architectural Membranes used for Tensile Membrane Structures). The use of tensile fabric is by no means a new concept, but the application of the material for permanent construction has only recently gained traction. Some of the first industrial uses of the construction method were seen in World War I, with the construction of temporary fabric hangars by the German Air Force. The structures were lauded for their mobility and ability to be erected quickly (Wilkinson). In the past fifty years, tensile fabric has been implemented in the permanent construction of highly visible structures such as sports stadia, airports, and shopping malls (P.D. Gosling a). The modern era of tensile fabric structures began with a small bandstand designed and built by Frei Otto for the Federal Garden Exhibition in Cassel, Germany in 1955. Prior to the use of computers, Otto pioneered the design of tension membrane structures with the use of physical scaled models (Richard Bradshaw). Due to the limited capabilities of materials during that era, the structure's spans were limited to roughly 80 feet (R. Shaeffer). It would take another two decades before the fabric structures saw significant in-roads to the permanent construction market (C. Huntington), (Berger), (R. Shaeffer).

Many experts agree that the modern North American fabric structures took off in 1970's at the completion of the US Pavilion in Osaka, Japan that was used for the World's Fair (C. Huntington), (Berger). The pavilion was an air supported structure that caught the imagination of engineers and architects. Shortly after the World's Fair in Japan, construction began on eight large sports stadiums throughout North America (Berger). During this same time, a team of engineers from Geiger Engineering and scientists at DuPont Owens and Corning Fiberglass created a new structural fabric known as Polytetrafluoroethylene (PTFE) (also known commonly as Teflon) coated – Fiberglass (Task Committee on Tensioned Fabric Structures). This fabric would be used in the eight previously mentioned stadiums since it boasted a higher durability and fire resistance than the currently used Polyvinyl chloride (PVC) – coated polyester (C. Huntington). At this point, the development of tensile fabric membranes for use in large permanent structures was limited by the ability to perform complex structural analysis. However, with coincidental accelerating advances in computer technology, the analysis required for the design of these structures became more accurate and far less time consuming (Koch), (C. G. Huntington).

Prior to the use of PTFE-coated fiberglass (PTFE/Glass), the main roadblock for fabric construction to enter into the permanent construction market was the combustibility of the currently used PVC-coated polyester (PVC/PES) (Richard Bradshaw), (Koch). With the use of PTFE/Glass, fabric rooves could be constructed with long life-spans, the benefit of non-combustibility, and increased light translucency (C. Huntington). The first successful project using PTFE/Glass was the University of La Verne Campus Center completed in 1972. As the pilot project for the material, DuPont Owens Corning had predicted a lifespan of 20 years. As of 2004, the original fabric membrane had remained in service, which was 40 years after its installation. This far exceeded the engineers' predictions (C. Huntington). In the mid-70's, there were several other iconic structures built as cases for the use of PTFE/Glass membranes, such as the Silverdome in Pontiac, MI, the Steve Lacy Field House at Milligan College, and the Thomas H. Leavey Activities Center at Santa Clara College in California (C. G. Huntington). The 80's saw further breakthroughs in the capabilities of tensile fabric structures with the introduction of insulated membranes in the Lyndsay Sports Centre in Calgary, Alberta, Canada, and the largest roof for any structure on the globe, which was achieved in Saudi Arabia with the construction of the Haj Terminal building at the Jeddah airport (C. Huntington), (Task Committee on Tensioned Fabric Structures). By the time the terminal building at the Denver International Airport was constructed in 1994, owners and builders were starting to see many of the unique benefits of using fabric in permanent construction. They were paying more for the roof material per square foot compared to conventional methods, but they would gain benefits such as significantly faster construction, a lighter roof structure resulting in smaller structural members and foundations, daylighting provided by a translucent roof, and generally lower maintenance costs (C. G. Huntington).

With an established reputation of providing structures that can safely stand the test of time, recently, experts in this field are focused on creating fabrics that correct weaknesses in leading materials. This includes reducing cost and increasing flame resistance, as well as focusing on the refinement of design with the increasing capabilities of computers (C. Huntington). There are several recently developed materials that vary in benefits to the fabric cladding, but due to issues in cost and geometric instability, the two primary materials used in the North American fabric architecture industry have remained the same over 40 years: PVC/PES and PTFE/Glass (C. Huntington). Advances in design of tensile fabric structures have been driven in part by the development of computer-based nonlinear structural analysis techniques that can more accurately predict behavior of the structures under loading (C. G. Huntington). Now that the tensile fabric construction industry has matured and become more accessible for customers such as the DoD, care must be taken to ensure that the DoD understands the differences in design and construction requirements for this new construction method to ensure projects are completed successfully.

Design Comparison

Since this section focuses on design, the core research question investigated here is whether or not steel framed fabric, when properly designed, is as structurally safe as conventionally constructed aircraft hangars. This section will begin by outlining relevant areas of UFC 4-211-01 *Aircraft Maintenance Hangar,* the core document used by USAF project managers, design and construction contractors, and AFCEC staff members for guidance on permanent hangar design and construction. The sections chosen from the UFC will be selected based on relevance to the design of steel framed fabric aircraft hangars. Once applicable sections are outlined, prevailing literature will be examined to shed light on any inconsistencies between DoD standards and best practices of the fabric construction industry. If practices and standards used in industry do not meet UFC requirements, this will also be addressed. Any best practices and industry standards that are not currently included DoD guidance will be highlighted here for support in later discussion of recommendations.

To begin the exploration into how steel framed fabric construction differs in design when compared to conventional construction, it will help to cover what the DoD requires of newly constructed aircraft maintenance hangars, by reviewing pertinent sections of the UFC 4-211-01. On page 1 of the UFC the authors state the following about the purpose of the document: “This UFC creates a single source for common DoD Aircraft Maintenance Hangar criteria and an accurate reference to individual Service-specific documents." In other words, this document should be the starting point for any USAF/DoD project manager that is beginning the design of an aircraft maintenance hangar. The UFC then proceeds to define what an aircraft maintenance hangar is, and its intended function. Some key points worth noting: activities in the hangar are taken to be short term and minor in nature as opposed to long-term overhaul activities, and the space within the hangar should be obstruction-free and surrounded on the exterior by supporting functions. It is also worth noting here that the UFC emphasizes the need to focus design on "facility safety, continuity of mission operations, flexibility, maximizing hangar bay utilization, and minimizing life-cycle costs of materials and systems."

Chapter 3 of the UFC is dedicated to general requirements of hangars that are applicable to all branches of service. It is here that most relevant requirements to the discussion of steel framed fabric construction can be found. Section 3-3.1.1 sets requirements for design based on fire prevention code in the NFPA 409. Within the NFPA 409, membrane-covered rigid-steel-frame structures are defined to be Group IV hangars, which set certain limits on floor area, height of the structure, and separation from other structures. Conventional construction often falls under either Group I or II hangars, which have less restrictions due to the NFPA since the construction materials are less combustible (National Fire Protection Association).

In addition to different facility sizing requirements NFPA 409 requires that the testing methods in NFPA 701 be used for membrane covered hangars, since those tests are applicable to fabrics. The rest of the section on Group IV hangars reads similarly to that of Groups I-II, just with more stringent limitations due to the construction type. In chapter 3 of the UFC, the IBC is also referenced assigning restrictions for building area and height. The IBC bases allowable building area and height on occupancy type of which aircraft maintenance hangars are considered S-1, storage occupancy group. The IBC allows for unlimited area if an automatic sprinkler system is installed according to the applicable code. However, this exception does not apply to membranes that do not meet non-combustibility requirements set out in the NFPA (International Code Council).

The next section of interest in UFC 4-211-01 sets requirements for the exterior envelope and refers the designer to UFC 3-101-01 *Architecture*. The purpose of UFC 3-101-01 is to serve as the minimum architectural requirements for typical architectural design services. Chapter 3 of this UFC sets out requirements for the building envelope such as requiring a waterproof barrier, air barrier, water drainage plane, and moisture barrier. Much of this section directs the facility designer to more specific requirements set out in the IBC. The discussion of building envelopes does not explicitly identify requirements for membrane clad structures, therefore examination of best practices and industry building code is required to show that requirements can be met. In addition to building envelope requirements, UFC 4-211-01 requires that designers account for how differences in temperature inside and outside the facility effect the structure. To maintain the conditions inside the hangar UFC 4-211-01 requires HVAC systems and components be sized to achieve a heating requirement of 55F at 99% dry bulb outdoor temperature inside the maintenance bay when occupied and 50F unoccupied.

Following the section on building envelopes in UFC 4-211-01, the UFC covers requirements for exterior walls and roof. The UFC establishes a unique requirement for aircraft maintenance hangars by mandating “masonry or concrete finish up to a minimum of 10 ft. (3.0 m) above the finished floor for the interior and exterior face of the entire perimeter of the Aircraft Maintenance Bay, except at hangar doors." This requirement obviously limits the use of membrane cladding to sections of the structure beyond the 10ft region unless there is some form of exception that can be made for tensile fabric construction. UFC 4-211-01 requires that roof systems are designed in accordance with (IAW) UFC 3-110-03, *Roofing,* which does not offer any specific direction that seems applicable to tensile fabric roofing. The roofing UFC does provide an extensive list of the acceptable roof systems to be used on DoD facilities, of which steel frame fabric is not included (Department of Defense).

The next section of UFC 4-211-01 pertinent to tensile fabric aircraft hangars requires aircraft maintenance hangars to be designed IAW UFC 4-010-01, *DoD Minimum Antiterrorism Standards for Buildings.* This UFC establishes minimum design requirements necessary to minimize risk of damage to DoD personnel and property in the event of a terrorist attack. It minimizes risk by setting separation distances between structures, blast reinforcement requirements, site layout requirements based on the type of construction and the level of occupancy of a facility. This UFC specifies that if a facility meets the requirements for "low occupancy" then it is actually exempt from the UFC's standards. UFC 4-211-01 has the following to say in regards to hangar occupancy levels:

> Aircraft Maintenance Hangars are generally considered "inhabited" buildings due to the occupancy and population density within the administration and office areas. However, the Aircraft Maintenance Bay may be considered "low occupancy" buildings if it meets all the requirements of UFC 4-010-01. (pg. 47)

UFC 4-010-01 defines low occupancy as a facility routinely occupied by fewer than 11 DoD personnel or a facility having a population density of less than one person per 430 gross square feet. This means that an aircraft maintenance hangar with a footprint of 200ft by 200ft (40,000 square feet) in the bay area is limited to 93 DoD personnel to be considered low occupancy. However, the aircraft maintenance hangar is commonly designed with supporting functions such as supply and admin offices either attached or housed within the facility. These supporting areas may or may not meet the requirements for low occupancy. UFC 4-010-01 requires sections of a building that do not meet low occupancy requirements to be structurally isolated from the low occupancy areas of that facility, so that the collapse of the low occupancy area does not cause the collapse of an inhabited area (Department of Defense).

Following antiterrorism requirements, the next relevant requirements in UFC 4-211-01 pertain directly to the structural design of the hangar. The UFC directs the designer to UFC 3-301-01, *Structural Engineering*, which is the DoD's adaptation of structural guidance outlined in the IBC directing the designer to relevant areas of the IBC as well as imposing requirements unique to DoD facility design. For the design of hangars, unique load cases such as bridge cranes, fall arrest systems, and hangar doors are highlighted. UFC 4-211-01 sets the limits for deflection of roof and wall structural elements to the criteria of L/240. Lateral drift of the facility is also restricted in this section which includes the drift of cladding such as tensile fabric. UFC 3-301-01 provides deflection and drift limits based on material used, but does not specify limits for tensile fabric cladding. This UFC does allow modification of the drift limits with approval from the authority having jurisdiction (AHJ) (e.g. for USAF projects the AHJ is usually AFCEC). As part of the serviceability requirements, UFC 3-301-01 also states that wall systems that are not part of the lateral force-resisting system shall be detailed such that they are not vulnerable to damage caused by the drift of the supporting structure.

Lastly, the UFCs mentioned above prescribe several of the DoD's established best practices relevant to the design of aircraft maintenance hangars. UFC 4-211-01 discusses vertical lift fabric doors (VLFDs) and prohibits their use in areas of the US and its territories that meet the criteria of a Wind-Borne Debris region, since the materials used do not meet the testing requirements for those regions. UFC 3-101-01 prescribes the best practice for permanently constructed buildings to use finishes, materials, and systems that show low maintenance and low life cycle cost over a life cycle of more than 25 yrs. However, UFC 1-200-02 requires that LCCAs are conducted on a study period of 40 yrs., so 40 yrs. will be used for the remainder of this paper as the more stringent requirement. UFC 3-101-01 also recognizes benefits of daylighting on productivity of building inhabitants and prescribes it as a best practice for facility design where feasible and life cycle cost effective (Department of Defense). These best practices conclude the sections of the UFCs relevant to tensile fabric construction.

To summarize, the sections highlighted throughout the UFCs cover requirements for fire protection and prevention, building envelope and HVAC design, wall and roofing design, structural design, antiterrorism standards, and recommended best practices. The following review of industry standards and best practices will follow a similar outline and include design considerations unique to tensile fabric clad aircraft hangars.

The 2015 IBC and ASCE/SEI 55-10 *Tensile Membrane Structures* are the industry building codes examined for comparison to the above guidance offered in the UFCs. The IBC section 3102 is dedicated to the design of tensile membrane structures with a service life of longer than 180 days. The IBC offers general guidance on design and also requires the designer to use ASCE 55 for tensile membrane structures. The two codes provide guidance applicable to fire protection, roofing, serviceability, design load analysis, and unique considerations for the design of tensile fabric structures. These codes do not however, prescribe new requirements for the building envelope, HVAC systems, exterior wall design, life cycle cost effectiveness, daylighting, and design against wind-borne debris. Additional guidance relevant to these topics will be sought out in the prevailing industry best practices section later in this chapter.

Beginning with guidance on fire protection, the IBC classifies noncombustible membranes as Type IIB construction. In general, this allows the material to be used for all major building elements of a facility that are allowed a zero-hour fire resistance rating. All other membranes are classified as Type V construction, which has much more limitations related to fire protection. ASCE 55 further distinguishes the levels of fire performance by setting the Class I, II, and III for the noncombustible, limited combustible, and combustible membranes respectively. Building area and height are limited similarly to what was discussed in the UFCs.

In regards to roofing design, the only guidance provided comes from the IBC, which permits the use of membranes as long as the roof is at least 20 feet above any floor level.

When considering the design of tensile fabric that acts primarily as a cladding, the requirements for deflection limits and serviceability become less stringent than if the material was used as a primary structural member. The IBC specifies that in this case, the membrane will not provide lateral restraint for the structural frame members, which is an important consideration for engineers designing the lateral force resisting system that the membrane covers. In addition, ASCE 55 does not set drift limits on framing that supports fabric structures because membranes are designed to relax throughout their lifespan. The only serviceability limit imposed is that the structure is detailed such that fabric cladding does not interact with rigid frame members throughout the life of the facility.

When it comes to design load calculation, much of the process for tensile fabric construction still follows the IBC and ASCE 7 methods typically used for conventional construction. There are, however, several differences and nuances that designers must focus on when determining structural design loads for tensile fabric construction. ASCE 55 stipulates that designers must consider the effects of localized snow loads due to sliding snow on the membrane. The designer must also account for the nonlinear geometric relationship between applied loads and structural deformation. Therefore, the assumption of superposition of load effects on the structure that is valid for linear elastic behavior of conventional construction is not valid for membrane design. When evaluating different load cases, ASCE 55 prescribes different life-cycle factors that account for the deterioration of fabric over time as well as the unique load case caused by prestressing used in tensile fabric construction. Lastly, during load analysis ASCE 55 requires that designers evaluate the strength capacity of fabric in both uniaxial directions of warp and weft as well as biaxial strength and tear strength capacity.

ASCE 55 offers additional guidance to the designer when designing tensile fabric structures that does not align with conventional design practices. This guidance includes: designing membrane structures to avoid disproportionate collapse, considering ponding due to the combination of losses in prestress and concentrated snow or rain loading, ensuring adequate prestress of fabric to avoid slack or zero tension areas, and that the design must include analysis of nonlinear behavior resulting from large deflections of material (American Society of Civil Engineers).

The literature examined from practicing structural engineers and leading researchers provided many best practices that closely align with what is prescribed in the above industry standards for constructing with tensile fabric. The ASCE Task Committee on Tensile Fabric Structures (TC on TFS) provides clarification on fabric fire resistance in their report titled, *Tensile Fabric Structures,* “All architectural fabrics for tensile structures are at a minimum fire resistive, however some are considered non-combustible (pg. 42).” This report also recommends that owners obtain documentation of fire test results from the manufacturer prior to accepting the material. Typically PTFE/Glass meets code requirements for noncombustible construction and PVC/PES at least meets fire resistive requirements (C. Huntington). Further distinction of material combustibility will be discussed later in the comparison of tensile fabric materials.

The IBC and ASCE 55 did not provide much direction on the building envelope properties of tensile fabric membranes, however guidance was provided in other published works from the industry. For tensile fabric structures, the building envelope is primarily provided by the membrane cladding itself. Protection from weather depends on the type of coating that membrane is manufactured with (Richard Bradshaw), (P.D. Gosling a). It is well recognized that fabric material used as cladding does not provide insulation by itself (Koch). If temperature control is needed for the given climate, then a minimum of two membranes is recommend to achieve adequate insulation levels (Task Committee on Tensioned Fabric Structures). Figure 2 shows the TC on TFS summary of thermal characteristics of the different types of membrane materials. For climates that require insulation to maintain heated and cooled conditions in a hangar, there are products that implement insulation between two layers of membrane which achieve R-values of R25 or R30 (Wright).

	Assembly No. / Properties	Assembly 1	Assembly 2	Assembly 3	Assembly 4	Assembly 5	Assembly 6
Solar	Reflectance	10-50%	30-75%	65-75%	60-65%	60-70%	60-70%
	Absorption	50-90%	13-68%	13-19%	12-20%	28-34%	28-35%
	Transmission	0	2-12%	6-22%	15-28%	4-6%	2-5%
U-value	Summer (12 km/h Wind)	Varies	0.75	0.81	0.81	0.45	0.08-0.14
	Winter (24 km/h Wind)	Varies	1.15	1.20	1.20	0.54	0.08-0.14

Assembly 1: Conventional Roofing
Assembly 2: PVC Fabric
Assembly 3: PTFE Glass Fabric
Assembly 4: Silicone/Glass Fabric
Assembly 5: PTFE Glass w/Liner & 250 mm Air Space
Assembly 6: PTFE Glass w/Translucent Insulation

Table 8-1
Solar and UV Reflectance and Absorption rates

Figure 2. Summary of thermal performance characteristics for different materials (Task Committee on Tensioned Fabric Structures) pg. 131.

Unlike conventional building envelopes the effects of indoor and outdoor temperature differentials do not significantly affect most membrane materials and therefore thermal effects to the membrane do not need to be considered in the design of the cladding (Shoemaker), (C. G. Huntington). Also, due to fabric’s varying translucency properties, the level of light transmittance can be changed to improve the thermal performance within the facility.

The UFCs and IBC layout clear guidelines for building serviceability and deflection criteria. Fabric membrane clad structures must still abide by the same codes as conventional structures, there are just unique considerations designers must be aware of when using this material (Rendely). When it comes to serviceability, a tensile membrane structure will maintain stability as long as the membrane remains in tension (Berger). Tension throughout the membrane is achieved by proper prestressing of the structure and the stability therefore depends on correct prestressing in addition to support from a stable superstructure (Richard Bradshaw). The supporting members of the membrane must be designed to maintain stability in the case that there is a significant tear or if the fabric goes slack in an area (Berger), (Rendely). Close attention must be paid to the interaction of the fabric and supporting structure. The connections between the fabric and supporting members should be rigid while the superstructure is allowed to deflect with hinge foundation connections (Koch).

As with serviceability and deflection requirements, the load analysis of a membrane clad structure must follow all of the same building codes requirements that a conventional structure does (Task Committee on Tensioned Fabric Structures). In load determination there are however trends that have led the fabric structure industry to accept certain best practices. Firstly, tensile membranes are much lighter than conventional building envelope materials and therefore imply a significantly lower dead load to the structure (Berger), (Task Committee on Tensioned Fabric Structures), (C. G. Huntington). Many have accepted that such a low dead load eliminates the need for seismic analysis (Task Committee on Tensioned Fabric Structures), (Berger). Typically for large surface area structures such as aircraft hangars wind loads are usually the controlling design load condition (Task Committee on Tensioned Fabric Structures), (C. G. Huntington). The downside of having such low self-weight is that usually tensile fabric structures do not have enough weight to resist uplift wind forces and therefore have to be anchored (C. G. Huntington). In addition to the traditional loads applied on structures, designers of fabric structures must account for localized sliding snow loads that have the potential to cause ponding (C. Huntington). Designers must also consider shear forces between fabric panels in the design of joint overlaps as well as the horizontal loads implied from the tensioned fabric on to its supporting members (Bradenburg, Architectural Membranes used for Tensile Membrane Structures), (Rendely).

The UFC 4-211-01 identified several best practices including considerations for wind-borne debris regions, life-cycle cost effectiveness, and daylighting. The suggestion to not construct VLFDs in wind-borne debris regions seems equally as valid for membrane cladding on hangars since architectural fabric is vulnerable to punching and cutting actions characteristic of wind-borne debris impact (Monjo-Carrio). With lifespans ranging between 10-30 years, tensile fabric structures have been shown to be more economically efficient than conventional construction in large span structures (Ben N. Bridgens), (Task Committee on Tensioned Fabric Structures), (C. G. Huntington). As was shown above in Figure 2, depending on the material used the level of daylighting can be controlled to meet the owners needs (Ben N. Bridgens), (Task Committee on Tensioned Fabric Structures). Many of the materials used also have reflectivity characteristics that aid in lighting the facility (Koch).

To end the design comparison several best practices unique to tensile fabric structures will be highlighted here. The greatest vulnerability of tensile membranes is being torn, which can quickly lead to structural failure of significant areas of the membrane. In order to avoid tears, careful detailing in design is required to avoid stress concentrations in the fabric (Richard Bradshaw), (Koch). Nonlinear finite element analysis must be incorporated into the design of fabric membranes (C. Huntington), (Ben N. Bridgens), (P.D. Gosling a). A structural engineer that specializes in the design of tensile fabric structures is typically used to account for the many unique characteristics of these structures. This specialty engineer should deliver drawings that include seaming, anchorage of the fabric, and highlight areas of the membrane that are reinforced against stress concentrations (Task Committee on Tensioned Fabric Structures). When designing fabric structures that take flat shapes, such as what is typically seen in aircraft hangar membranes, the design must ensure that the flat panels maintain their shape through proper prestressing to avoid ponding (Ben N. Bridgens). When using flat membranes, the membrane must be supported at relatively close intervals by the rigid frame. In these cases the fabric span is typically limited to 33ft (C. G. Huntington).

Much of the discussion on structural performance above revolves around the use of fabric membranes as a primary load resisting member of the structure. In the application of aircraft maintenance hangars for the USAF a fabric membrane would simply be a cladding that is supported by self-supporting structural frame. The literature explored here does not explicitly provide structural analysis of fabric membranes acting as a cladding on a steel frame. For this unique case of tensile fabric construction, a structural comparison of fabric to conventional is needed to clearly demonstrate that the new cladding system can provide the same structural safety as conventional construction for an aircraft maintenance hangar. Additionally, the literature does not explore loading and design requirements implied by the UFC when designing for the USAF. Therefore, this research will perform a 3D modeled structural analysis of fabric membrane and standing seam steel clad aircraft maintenance hangar according to UFC design requirements. As recommended in the literature, this analysis will consider non-linear mechanical behavior with the aid of the ABAQUS 3D finite element analysis software (Task Committee on Tensioned Fabric Structures).

Comparison of Construction Methods

One of the main draws to using tensile fabric structures is that construction is usually quicker than a comparable conventional structure (C. Huntington), (Berger), (Kronenburg). For the USAF, this perceived benefit is especially appealing since a shorter construction timeline implies more flexibility for mission execution. With a zealous rush to construction methods that free up time for the USAF project manager, there needs to be an awareness of major differences in construction procedures to ensure project success. The core research question investigated in this section is whether or not steel framed fabric is practical to be constructed on USAF installations. In addition, this section will provide support in answering the question of whether over a life-cycle of 40 years, steel framed fabric is more cost effective than conventional construction for aircraft hangars. This section will begin by briefly illustrating the typical order of operations for constructing a tensile fabric structure. Then, the attributes unique to tensile fabric construction will be highlighted such as items of concern during inspection, contractor availability, common construction errors by either the installer or owner, and typical sources for delay. The section will conclude by discussing industry trends in construction duration and cost compared to conventional construction.

Prior to materials arriving on-site, a crucial step in fabric construction is manufacturing or fabrication of the membrane off-site (Koch), (Task Committee on Tensioned Fabric Structures). The membrane is prefabricated at an off-site location according to the design geometry provided by engineers. In most cases, this requires the fabricator to be familiar with and have access to 3D modelling software that was used to design the membrane (Koch). During fabrication, quality control of the final membrane shape is key to ensure accurate conformity to the intended design geometry (Koch), (Task Committee on Tensioned Fabric Structures) . Maintaining the correct shape will ensure that the membrane will perform as intended when the design prestress load is applied. After fabrication, due to the lightweight and flexibility of the fabric, the membrane can be carefully folded and easily shipped in containers to the construction site (Berger).

Construction of tensile fabric structures proceeds in three phases: layout of the fabric and supporting materials, fastening, and tensioning (Task Committee on Tensioned Fabric Structures).

Layout

Upon arrival, the membrane is carefully laid out in panels on one side of the main structure according to the warp and weft orientation within the fabric weave (C. G. Huntington). The size of the panels depends both on the design and seam layout as well as the fabric used. For example, PVC/PES is limited in panel width to 1.5 to 2 meters between seams and PTFE/Glass is limited to four meters in width (C. G. Huntington). This is where the experience of a structural engineer that specializes in fabric construction is useful in coordinating the design seam directions and panel size with planned construction procedures (Monjo-Carrio).

Fastening

During the fastening phase of construction, for structures that have self-supporting frames, the membrane is pulled over the frame similar to what is shown in Figure 3.

Figure 3. Fastening of one end of a membrane to the finished steel frame structure. Pg. 149 **(C. G. Huntington)**

An additional benefit, also shown in Figure 3, is that membranes can be fastened with the use of hydraulic man-lifts instead of costly scaffolding (Berger). As the fabric is fastened to the supporting structure, the panels are jointed together using either high frequency welding or stitching depending on the type of material. The seams that form in this process must be aligned precisely and fixed in place to maintain correct position of the membrane during jointing (Koch). For large projects, many personnel, but minimal amounts of equipment, are needed during the membrane erection process to maintain accurate positioning (C. G. Huntington).

Tensioning

The tensioning phase of construction can begin shortly after fastening has begun since the fabric panels are typically prestressed as soon as they are in position. The panels are prestressed orthogonally to the seams and secured into their final installation points. Installation crews must pay close attention to the rate of prestressing, which should be gradual and uniform, until the membrane reaches the prescribed design stress (Task Committee on Tensioned Fabric Structures).

Every conventional cladding system has inherent details that require unique quality control measures to be implemented by engineers, installers, and manufacturers throughout construction to ensure the structure is built and performs as designed. This is no different for tensile membrane structures. Project success for tensile membrane structures begins with establishing accurate material properties prior to design in order for engineers to prescribe the correct prestress for membrane stability (Ben N. Bridgens). Obtaining accurate material properties requires manufacturers to test fabric according ASCE 55, which requires membranes to be tested per ASTM D4851 (American Society of Civil Engineers). Many builders and engineers recommend that manufacturers and installers have documented experience relevant to the type of structure that is being built (Pfeiffer Guard-All Inc), (Rubb Buildings LTD), (C. G. Huntington). This experience includes a proof of successful fabrications by the manufacturer, having at least an experienced superintendent to lead the erection of the fabric structure, and an experienced designer that can show success in similar structures. As was noted above, a final erected shape that conforms to the design geometry of the membrane is crucial to a successfully constructed fabric structure. For that reason, contractors recommend that design drawings include size and shape of membrane, type and location of connections, and type and extent of all heat-welded seams (Pfeifer Guard-All Inc.). It is also recommended that the builder employ methods to monitor the geometry of fabric throughout construction, because some fabrics demand a tight tolerance between the designed and final construction geometry of the membrane (Pfeiffer Guard-All Inc), (Task Committee on Tensioned Fabric Structures). One reason stated for the demand of installer experience is the process of prestressing. In order to apply prestress at the correct and uniform rate requires an experienced eye to monitor the behavior of the fabric (Ben N. Bridgens).

Contractor Availability

Due to requirements set out in the Federal Acquisitions Regulations (FAR), the USAF must promote full and open competition when sourcing construction projects (Department of Defense). Therefore, the practicality of building aircraft maintenance hangars with tensile fabric membranes on an AFB is greatly affected by the availability of contractors that are technically qualified to perform this task. When it comes to steel framed fabric structures the industry is highly competitive and contract selection is cost-driven (C. Huntington). However, fabric construction, in general, controls a relatively small market share of the construction industry. The majority of fabric structures projects are completed by a combination of a steel erection contractor and a fabric manufacturer (Kaltenbrunner). The industry preference is to execute these projects through a design/build approach, which enables a contractor to maintain a staff of specialized engineers throughout the design and construction process. However, if the owner is limited to a design/bid/build approach to make the project more competitive, it is recommended that a specialized structural engineer is retained for both the design and construction phases of the project (C. G. Huntington).

Scheduling

One main concern when constructing for a USAF or DOD customer is schedule duration. Therefore, it is important to discuss whether or not fabric construction can deliver products faster than conventional construction. As the tensile fabric construction industry has grown and developed, it has been shown that the erection time of a fabric structure is significantly shorter than a comparable conventional structure (Berger), (RUBB Building Systems), (Kaltenbrunner), (C. Huntington), (Beccarelli). Lightweight materials, which result in quicker transportation and less erection equipment, are largely to blame for quicker assembly (Kaltenbrunner), (Berger). Fabric construction also has minimal sources for delay, which are dependent primarily on wind conditions and extremely cold temperatures. Typically, if the membrane is not secured, assembly operations should be stopped when winds are above 15mph (Task Committee on Tensioned Fabric Structures). Also, it is recommended when using PTFE/Glass for the membrane, at temperatures below negative five degrees Celsius, care must be taken in material handling because it tends to become more brittle (Ben N. Bridgens), (Koch).

Cost

Another leading concern for USAF customers is cost. Similar to any type of construction, the cost of fabric construction varies depending on complexity of design and type of material used (Task Committee on Tensioned Fabric Structures), (C. G. Huntington). Costs can vary between $400 and $1700 per square meter for the finished structure (excluding site work, electrical, mechanical, plumbing, and foundation work) (C. G. Huntington), (Task Committee on Tensioned Fabric Structures). However, when the structures are simplified with standardized design, similar to what is seen in large warehouses and hangars, the cost is lowered to as little as $250 per square meter (Task Committee on Tensioned Fabric Structures). The primary reason for this reduction in cost in comparison to conventional structures, is credited to the relatively light weight roof and wall materials of a membrane structure and the resulting smaller structural and foundation systems (P.D. Gosling a).

It is clear that fabric construction has desirable qualities when compared to constructing a conventional structure that would benefit the USAF. The literature generally agrees that compared to conventional construction methods, fabric structures are constructed quicker and at a lower relative cost. However, the simple rectangular steel framed fabric aircraft hangar that would be used by the USAF, has not been closely examined in the literature. Per UFC 1-200-02, when examining construction alternatives, the USAF requires the use of a 40-year LCCA comparing the alternative to the status quo (Department of Defense). This research will gather historical cost data from several contractors in the steel framed fabric construction industry to develop an LCCA comparison to conventional construction.

As with cost analysis, the literature explicitly covers the construction process for tensile fabric structures in general, but provides minimal detail on typical processes for construction of large steel framed fabric structures such as would be used for aircraft maintenance hangars. Through case study interviews with contractors and existing hangar owners this research will form a narrative of construction methods used on fabric aircraft maintenance hangars. Similar qualitative methods have been used by researchers to understand construction procedures used for more complex fabric structures such as stadium rooves (Nunes). Since the concept of using fabric construction for permanent structures is relatively new to the USAF, case study research is the recommended method for gaining initial holistic understanding of an idea (Baskarada, Qualitative Case Study Guidelines). By capturing these experiential accounts the USAF can better understand how steel framed fabric could be practically implemented in the construction of aircraft maintenance hangars.

Comparison of Maintenance

A similar approach to what was seen in the construction discussion will be taken in examining differences maintenance of tensile fabric structures and conventional structures. The comparison of maintenance procedures also provides support in answering the research questions of practicality of tensile fabric aircraft hangars permanently constructed on AFBs. Maintenance requirements can often be the determining factor for USAF leaders when deciding between construction alternatives, primarily because maintenance of installation facilities is the responsibility of the assigned USAF civil engineering personnel. Specifically, this section will focus on common maintenance concerns for fabric structures, typical service life, how maintenance is performed, and trends in maintenance cost.

Common Maintenance Concerns

UFC 3-110-03 defines maintenance as, “The proactive efforts expended on a recurrent, periodic schedule that are necessary to preserve the condition of the roof components and systems as they were designed for their anticipated service life (Department of Defense).” Proceeding with this definition in mind, conventional structures, depending on the type of roofing that is used, have several common maintenance tasks. These include: membrane repairs, flashing inspection and repair, cleaning debris from roof drains and gutters, checking and repairing roof blisters, maintaining pitch pockets, and re-caulking seals (Bradford), (Division of Capital Construction), (National Roofing Contractors Association). In general, fabric membrane rooves require less maintenance than conventional rooves (Berger), (C. G. Huntington). The amount of recommended maintenance depends on design, material used, and location (Koch), (R. Shaeffer), (C. G. Huntington), (Wang, Abdul-Rahman and Wood). The primary maintenance requirements of tensile membrane structures are re-tensioning the membrane through tension cables, membrane cleaning, and repair of tears with the use of patch kits (C. G. Huntington), (Monjo-Carrio). Re-tensioning is recommended depending on the material used, to ensure that the membrane does not have areas of slackness. For materials that require it, re-tensioning is recommended one year after installation due to fabric adjusting to environmental loading of the location. Then, regular re-tensioning should occur every two years depending on the material used (Monjo-Carrio). Cleaning of membranes is recommended only when the location has high pollution levels or climates that produce corrosion and/or the functions within the facility have by-products that soil the membrane. Some membrane materials are manufactured with a self-cleaning coating which eliminates this requirement completely (Koch), (C. G. Huntington), (Monjo-Carrio), (Wang, Abdul-Rahman and Wood). Early identification of tears and tear initiation has been shown to extend the life of a tensile membrane (Monjo-

Carrio). Once identified, owners or maintenance personal can repair the tear with the use of repair patch kits usually provided by the installing contractor (Pfeiffer Guard-All Inc), (C. G. Huntington). Lastly, it is recommended that owners establish an annual inspection service to identify the preventative maintenance requirements listed above (C. G. Huntington), (Monjo-Carrio).

Service Life

Typical service life and the warranty period of tensile fabric membranes depend on the material used. Specific lifespans of each available material will be examined in the next section on commercially available fabrics. Overall fabric membranes have been shown to have lifespans of 15-30 yrs. (Koch), (Task Committee on Tensioned Fabric Structures), (Ben N. Bridgens). For conventional construction there is a wide range of estimated service life depending on the specified roofing system. Common conventional roofing systems include: built-up rooves (BUR), single-ply membrane, ethylene propylene diene monomer (EPDM), asphalt, and metal rooves (Coffelt and Hendrickson), (Kalinger), (Russ). Low slope rooves such as BUR, membrane, EPDM, and asphalt have average service lives that range from 15 – 30 years (Coffelt and Hendrickson), (Kalinger). Steep rooves, like standing seam metal rooves (SSMR) that are often used in the construction of aircraft maintenance hangars, have service lives that range between 30-75 years (Coffelt and Hendrickson), (Russ). Therefore, conventional rooves have a longer service life than fabric membrane rooves. This raises the question: over the lifetime of fabric rooves how does the maintenance cost compare to that of conventional rooves?

Cost

The examined literature lacked explicit cost data for annual maintenance costs on fabric structures, but it could be inferred qualitatively, that there is relatively less maintenance to be performed on fabric structures, and that therefore the annual maintenance costs are lower than conventional structures. To support this inclination, this research will compile data from several contractors that provide maintenance services. This data will then be incorporated into the LCCA comparison to conventional structures.

Additionally, since the literature does not directly discuss the maintenance of tensile fabric membrane aircraft hangars, the case study performed in this research will interview owners and facility managers of existing aircraft hangars to provide a narrative of their experience maintaining and operating these type of hangars in comparison to conventionally constructed aircraft hangars.

Commercially Available Fabric Material

The last area of interest in the literature, is assessing the currently available types of architectural fabric that are used to manufacture tensile membranes. By identifying trends throughout relevant literature, this section will support later recommendations for the types of fabric that are feasible for use in permanent aircraft maintenance hangars. This section will compare traits of each fabric such as strength, durability, cost, maintenance, and combustibility as was seen in the literature.

Materials used in the fabric construction industry are categorized by types of material used in both the scrim and the coatings of the membrane. Since the development of PTFE/Glass in the 1970's, PTFE/Glass and PVC/PES have been the two most widely used types of membrane in the industry (C. G. Huntington), (Ben N. Bridgens), (Koch). PTFE/Glass is composed of a fiberglass scrim and PTFE (also known commercially as Teflon) protective coating. PVC/PES uses a polyester scrim with a PVC coating. The industry has attempted over the years to modify these materials to either improve their structural performance or reduce costs, but they have remained popular due to low cost in the case of PVC/PES and long lifespans of PTFE/Glass (C. G. Huntington). The industry has established that, there is no one best fabric for every situation, but that fabrics must be chosen based on consideration of customer requirements and the strengths and weaknesses of each type of fabric (Task Committee on Tensioned Fabric Structures). Klaus-Michael Koch summarizes these strengths and weaknesses for many of the industry's available material options, below is an excerpt from the table shown on pg. 21 of *Membrane Structures: The Fifth Building Material*:

Fabric Type	*Use in roofs, facades and building envelopes*	*Special Properties*	*Fire Rating* *+ = low flammability* *++ = noncombustible*	*UV light resistant* *++ = excellent* *+ = good*	*Lifespan (years)*	*Self-cleaning property* *++ = excellent* *+ = good* *0 = under research*	*Strip Tensile Strength (N/5cm)*	*Recyclability* *++ = excellent* *+ = good* *0 = neutral*	*Recommended Temperature Range (deg C)*
PVC/PES	Permanent + mobile, internal + external	Standard material w/ a wide range of applications	+	+	15-20	+	2000 – 10000	+	-30 to +70
PTFE/Glass	Permanent, internal + external	High-quality standard material, fabrication is technically demanding	++	++	>25	++	1000-8000	0	All temperatures
Silicone/Glass	Permanent, internal + external	Tendency to soil when used externally	++	++	>20	0	1000-5000	0	All temperatures

Table 1 Excerpt from table comparing attributes of common structural fabrics **(Koch)**.

Silicone coated fiberglass was included in Table 1 because it has recently gained use due to a similar lifespan to PTFE/Glass at a lower cost (Eltahan). Table 1 provides a preliminary comparison of these materials, further examination of the each material will follow.

Beginning with PTFE/Glass, this material has proven to be reliable for permanent structures that require the membrane to provide significant strength and stability. Prior to DuPont and Owens Corning's development of PTFE/Glass, owners did not consider fabric construction a viable method for permanent facilities (C. Huntington). PTFE/Glass has advantages of high tensile strength at 3500 MPa (greater than commercially available structural steel), non-combustibility, PTFE's high resistance to ultra violet (UV) degradation and self-cleaning ability, and a long lifespan that averages 30 yrs. (C. G. Huntington), (C. Huntington), (Bradenburg, Architectural Membranes used for Tensile Membrane Structures). Since PTFE/Glass meets NFPA noncombustible requirements, the material has a lot of flexibility in the type of construction it can be used (C. Huntington), (American Society of Civil Engineers). High strength also means that material shows minimal deflection during operation and often eliminates the maintenance requirement for re-tensioning throughout the life of the structure (C. G. Huntington). Much of the disadvantages associated with PTFE/Glass are due to the brittleness of fiberglass. Brittleness causes vulnerability to tearing during handling and installation which requires workers to handle the material with great care. PTFE/Glass is vulnerable to tears and tear propagation since the material lacks the ductility to relieve stress concentrations effectively (C. G. Huntington), (C. Huntington), (Ben N. Bridgens). Lastly, PTFE/Glass is known for being relatively expensive for fabric materials. Typically a finished fabric roof costs $500 to $1000 per square meter which is three to five times the cost of PVC/PES rooves (C. G. Huntington), (Bradenburg, Architectural Membranes used for Tensile Membrane Structures).

Before PTFE/Glass was developed, the standard for tensile fabric construction since the early 1960's was PVC-coated polyester (Task Committee on Tensioned Fabric Structures). When fabric construction was in its infancy, structures were constructed for temporary purposes such as conventions where they would be erected for an event and then taken down after a short period (Wilkinson). The ductility that is characteristic of PVC/PES made it resilient to regular folding and unfolding (C. G. Huntington). Flexibility and low shear stiffness reduces this material's vulnerability to wrinkling, damage during handling and installation, and tear propagation. In addition, design margins for error are not as stringent due to membrane relaxation throughout the structure lifespan (Ben N. Bridgens), (Bradenburg, Architectural Membranes used for Tensile Membrane Structures), (C. G. Huntington). Even with relatively high ductility, PVC/PES maintains considerable tensile strength at 200 to 1000 lb./in in tensile strip strength (PTFE/Glass has a strip tensile strength of 500 to 1000 lb./in) (Bradenburg, Architectural Membranes used for Tensile Membrane Structures). The largest factor for PVC/PES continued use is its relative low cost due to low material cost and less need for precision and care during fabrication and construction (Ben N. Bridgens), (C. G. Huntington). One of the drawbacks to PVC/PES is a shorter lifespan of approximately 15 years since the membrane is less resistive to UV degradation than PTFE/Glass (Ben N. Bridgens), (Bradenburg, Architectural Membranes used for Tensile Membrane Structures), (C. G. Huntington). Also, PVC/PES is considered a limited combustible material according to

NFPA 701 which places restrictions on its use for high occupancy buildings (Ben N. Bridgens), (Bradenburg, Architectural Membranes used for Tensile Membrane Structures). Lastly, depending on the design of the structure, the flexibility and associated fabric relaxation over its lifespan typically requires PVC/PES membranes to be periodically re-tensioned throughout their lifespan as was described in the maintenance discussion above (Ben N. Bridgens), (C. G. Huntington).

Although PVC/PES and PTFE/Glass are the leading materials in the industry currently and are likely what will be available to USAF project managers, it is worth mentioning recently developed materials that could soon gain popularity in the market. Silicone-coated fiberglass was recently developed to address the high-stiffness and high cost disadvantages of PTFE/Glass while maintaining long lifespans and non-combustibility (C. G. Huntington). It has successfully performed as a more ductile material, which reduces vulnerability to tearing. Additionally, Silicone/Glass has proven to be less expensive than PTFE/Glass, but more costly than PVC/PES. Lifespans of Silicone/Glass have averaged 25 years. Because it is noncombustible, the material allows for more design flexibility with permanent structures (Task Committee on Tensioned Fabric Structures). However, there has been difficulty with construction. Silicone/Glass joints cannot be heat welded and require either adhesion or sewing (C. G. Huntington). Aramids are another recent development that aimed at improving on PTFE/Glass. They have been shown to have higher flexibility and are noncombustible, but they are less resistive to UV degradation. More importantly, Aramids are more expensive to manufacture than PTFE/Glass (Task Committee on Tensioned Fabric Structures).

Based on the above characteristics of PTFE/Glass and PVC/PES in the fabric construction industry, this research will provide recommendations for the application to steel framed fabric aircraft maintenance hangars that is practical for the USAF.

III. Methodology

Chapter Overview

This chapter gives the procedures used to conduct this research. It will describe the three primary methods of research: the qualitative case study, computer-based finite element analysis, and the life-cycle cost analysis (LCCA) comparison of conventional to steel framed fabric aircraft hangars. This includes description of theory, the participants, system inputs, environmental conditions, and controls used for each method. Possible biases and shortcomings for each method will also be addressed.

Instrumental Case Study

Fabric construction has developed to where there are several cases of airports and civil authorities that have adopted it as an effective solution for aircraft hangars. However, the USAF has not had much experience and is hesitant to use it for permanently constructed aircraft hangars. With the use of a case study an "in-depth appreciation of an issue in its real-life context" can be provided to the research audience (Sarah Crowe). In general, a case study is a method used to gain a holistic understanding of an issue by exploring a small number of cases in great depth and detail (Sarah Crowe), (Pamela Baxter). A case study is often justified when there is a need to understand participants' experience with an issue, such as facility managers' experience with operating tensile fabric aircraft hangars (Pamela Baxter). This qualitative analysis is what USAF leadership needs to gain an understanding of the practicality of implementing fabric construction in permanent aircraft hangars.

There are many types of case studies, such as exploratory and instrumental, that are useful in researching a theory that is new to an organization such as tensile fabric construction for the USAF (Maggi Savin-Baden). Exploratory studies are used when the researcher does not have enough existing support to develop meaningful questions. Instrumental case studies refine the understanding of a theory and they use observation, interviews, and data collection as the primary means of research. In the case of constructing aircraft hangars for the USAF, there is a breadth of research and experience to pull from industry and the government to develop meaningful questions when researching a new construction method. Instrumental studies are also intended to be used to support the rest of a research effort (Maggi Savin-Baden). For these reasons the instrumental case study was chosen over the exploratory method. The approach used in this research can also be characterized as a collective case study, where multiple cases are used to generate a broad understanding of an issue through the similarities and differences of each case (Sarah Crowe), (Pamela Baxter).

In case study research the unit of analysis is known as the case (Pamela Baxter). The case is research that must be answered in the case study, and here the question to be answered is: "How practical are steel framed fabric aircraft hangars for use in the USAF when compared to conventionally constructed aircraft hangars?" For the sake of not trying to answer too broad of questions in this study, the cases were bound to focusing on the design, construction, maintenance, and operation of permanently constructed aircraft hangars. The primary source for data collection in the case studies was interviews.

Participant Selection

The participants were chosen in such a manner that would draw from existing knowledge of hangar construction in the USAF. The key criterion being experience in design, construction, maintenance, and operating hangars for both conventional and fabric construction. This case study can be categorized by the three groups of participants that were selected to cover the study's scope. The first group is comprised of USAF civil engineers, including staff members with decades of experience in USAF construction, as well as recent aircraft hangar construction project managers. These participants were interviewed with the intent of developing a clear understanding of USAF needs for an alternative to conventionally constructed hangars. The second group includes contractors and manufacturers in both the fabric and conventional hangar construction industries. The focus here is to interview the contractors that would likely work with the USAF or DoD, and develop an understanding of how design, construction, and maintenance is performed on fabric hangars in comparison to conventional hangars. The last group is directed at owners and facility managers of existing tensile fabric hangars. The participants in this group were chosen to provide insight into how these facilities impact operations of the aircraft and personnel that inhabit them, as well as providing further detail on maintenance.

Given that instrumental case studies are intended to be loosely structured in nature, the type of questions asked were generally consistent for each the participants within a single group, but the follow-up questions and discussion depended largely on how participants responded to the initial question set (Maggi Savin-Baden). Many of the questions used for the USAF participants were general in nature (i.e. not focusing on design, construction, or maintenance). A sampling of the questions used in this group are shown below:

Why is the USAF interested in these type of structures?
Why would the USAF try to find alternatives to conventional construction?
How does fabric construction differ from conventional construction in execution?
Is the USAF hesitant about using fabric construction? And if so, why?

Table 2. Sample of questions used in interviews with USAF personnel group

The group that included contractors had questions focused primarily on design, construction, and maintenance practices for fabric vs. conventionally constructed hangars. A sample of the questions used are shown below:

Why was this type of construction chosen in design?
Did difficulties arise during construction? If they did, what were they?
Does QA/QC differ when constructing fabric hangars vs conventional construction methods/projects? If so, how?
Are there different maintenance concerns for fabric hangars vs conventional? If so, what are they?

Table 3. Sample of questions used in interviews with contractor group

The owners and facility managers were interviewed in person at their respective facilities. These interviews focused on understanding their experience with operating and managing the facilities, as well as capturing noticeable differences in the hangars from facility walk-throughs. These differences were captured in written notes and photographs taken during the walk-throughs. Below is a sample of the questions used to interview this group.

What level of training is required to adequately manage the facility?
Are there changes that have to be made to the way users operate within the hangar compared to a conventional hangar? If so, what?
How much downtime has maintenance caused?
What kind of warranty comes with the facility?

Table 4. Sample of questions used to interview facility managers.

At the beginning of each interview, participants were asked a series of questions that were used to develop a sense of the individual's background and past experience with hangars and/or fabric construction. This includes questions such as "What is your experience with these types of structures?" "What do you like about the structure?," and "What would you change if you could about the structure?" Additionally, questions were given to several participant groups depending on participants' knowledge of the topic discovered through prior screening. For example, many of the facility managers were able to answer design questions such as, "Why was this type of construction chosen in design?"

Since qualitative research is largely subject to characteristics of the participants in the study, there are many factors that were anticipated to effect this case study (Baskarada, Qualitative Case Study Guidelines). One key factor was experience. As was seen with many of the USAF personnel, the experience was very limited. This guided the type and number of questions that could be asked. Another factor is the personal/business interests that some participants had in the fabric industry or hangar construction industry, which was evident in the responses from the contractors. Lastly, the researcher's own familiarity with the subject matter through research played a key role in discussion with participants as the case study progressed.

Two primary recording methods were used to collect audio during interviews. All interviews were recorded using applications that were installed on the researcher's personal phone. For phone interviews, calls were recorded through the Call Recorder application by Call Team® available on the Google Play application store. In-person interviews were recorded using the Voice Recorder application by quality apps®. Audio files were then downloaded for playback and transcription of key points from each conversation.

With all interview data compiled, analysis of the case study proceeded by using the constant comparative method (CCM) to find common themes among the responses from participants to produce a narrative on the practicality of the USAF constructing tensile fabric aircraft hangars (Baskarada, Qualitative Case Study Guidelines). Additionally, responses will be assessed for distinct disagreements. The trends of similarities and disagreements between responses will be analyzed and discussed in the final chapter of this paper.

Structural Analysis

The next analysis of the research compares the structural safety of a steel framed fabric aircraft hangar to a USAF accepted method of construction. It is common for engineers to make use of structural analysis software to efficiently perform calculations required in structural design. With the development of computers, finite-element analysis (FEA) has developed into an accepted method for analyzing complex structures, such as large aircraft hangars (Task Committee on Tensioned Fabric Structures). One of the strengths to using FEA is that non-linear materials, such as tensile fabric, can be modeled. ASCE 55 requires tensile membrane structures to be analyzed with consideration of the material's nonlinear behavior (American Society of Civil Engineers). Therefore, FEA was the chosen method for structural comparison of the two types of construction. The Abaqus CAE © software by Dassault Systems ® was chosen as the vehicle to conduct the analysis. There are cases of the software being used in professional design of large aircraft hangars such as the Cargolifter hangar constructed in Brand, Germany (H. Pasternak, The Steel Construction of the new Cargolifter Airship Hangar).

In general, this comparison will create two simplified models of an aircraft hangar to be analyzed within Abaqus. The analysis is focused primarily on the performance of the hangar cladding used in each case. Performance will be judged based on the von Mises failure theory which compares the uniaxial yield strength of a ductile material to that of effective shear stress quantified by octahedral shear stress (Dowling). This relationship is shown in the below equations.

$$\overline{\sigma_H} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + (\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)} \qquad (1)$$

$$X = \frac{\sigma_o}{\overline{\sigma_H}} \qquad (2)$$

Equation 1 defines the octahedral shear stress, also known as the von Mises stress, in terms of the axial stresses in each of the Cartesian directions, σ_i, and shear stress represented by the $\tau_{i,j}$ terms. Equation 2 is the ratio of the material's uniaxial yield strength over the von Mises stress, also known as the safety factor. This safety factor will be what is sought after in each of the FEA models.

Each model will be created based on design documents provided by AFCEC for a KC-46 hangar to be constructed at Tinker AFB, OK. The Tinker hangar is clad with a combination of corrugated steel sheeting and concrete masonry with a standing seam metal roof. The design of the KC-46 Tinker AFB hangar was chosen as a starting point for comparison for multiple reasons. The location provides environmental loading that is typical of many AFBs throughout the central region of the US. The size of the hangar is relevant to the research of large aircraft hangars with spans of more than 190ft.

The primary focus in the structural analysis is the performance of the cladding. Therefore, the structural frame of the Tinker hangar was used for both the fabric and conventional models. To simplify the models, only two bays of the hangar frame were used. Cladding for the conventional hangar was modeled with loads transferred from the steel cladding to the supporting frame. Further explained in the next chapter, the conventional model is simply the hangar frame, unclad, with superimposed loading on the frame. The fabric model was clad with membrane elements that have equivalent properties to the PTFE/Glass product known as Sheerfill®, manufactured by Saint-Gobain © (Saint-Gobain Performance Plastics). The steel frame in each model was meshed primarily with 3D linear beam elements, labeled as B32 within Abaqus. The cross sections assigned to each of the steel members correspond to the members used in the Tinker AFB design. The fabric membrane was meshed with 3D, four-node, reduced integration membrane elements known as M3D4R. Prior to assembling the fabric model, a convergence study was performed with a simple rectangular membrane section loaded with a pressure to ensure that the density of meshed elements could accurately model the behavior of the membrane under loading. By using a mesh density of 0.09 elements per square foot, the convergence study predicts a confidence level of 95% with a standard deviation of 4.3 inches for displacement results and 12009 psi for von Mises stress results. A summary of this study is included in the Appendix B.

With the models assembled, the next step was applying the various loading conditions required by the IBC, ASCE 7, and the UFCs. Design load determination followed a similar process to what was shown in the design documents provided by AFCEC. The dead loads and seismic loads were determined by the material weights provided, and wind loads were determined by the components and cladding method in Ch. 30 of ASCE 7-10. Once loaded, each of the claddings used in the models were analyzed to determine safety factors based on the von Mises failure criteria explained above.

Life Cycle Cost Analysis

The final aspect of this research will be conducted IAW UFC 1-200-02, which mandates the use of Building Lifecycle Cost (BLCC) 5 program for lifecycle cost analyses (LCCAs) (Department of Defense). This LCCA comparison will focus on cost associated with a hangar constructed in Oklahoma City, OK in the year 2018. Within

BLCC 5, the life cycle comparison method will be used to compare a conventionally constructed aircraft hangar as the status quo to the alternative of a steel-framed fabric hangar. The footprint of 50,190 square feet used in the structural analysis will be assumed for the LCCA. Inputs for the analysis will be estimated costs per area provided by USAF and DoD historical data for conventional hangars, and data provided by fabric industry contractors for steel framed fabric hangars.

Given the amount and quality of cost data that was able to be obtained in this research, the estimates conducted most closely align with the Square Foot/Square Meter Estimate that is outlined in UFC 3-740-05, *Construction Cost Estimating Handbook.* This method relies on the relation of costs for major facility components with the calculated floor area of the facility. According to UFC 3-740-05, this type of estimate is accurate between -15% and +25% of the actual construction cost (Department of Defense).

The data obtained for conventional hangars is available in UFC 3-701-01, *DoD Facilities Pricing Guide.* This UFC compiles historical data from across the DoD on different facility types and is typically used as a resource for USAF programmers for macro-level budgeting analysis. Therefore, it is limited in its accuracy for individual facility estimates. The utility of UFC 3-701-01 is in providing average costs, which can be adjusted for area cost factors (ACF) and annual escalation rates. The inputs provided by the fabric construction industry were obtained from several of the participants in case study interviews. Data was provided in the form of unit cost per square foot estimates, annual maintenance cost estimates quoted in interviews, and final construction cost estimates provided to facility owners.

These unit costs will then be multiplied by the hangar area for input into BLCC 5. As per the business rules outlined in UFC 3-701-01, the estimates obtained for construction cost were estimated based on the formula for plant replacement value shown below, and then multiplied by the military cost premium for aircraft maintenance hangars (facility assessment code 2111) (Department of Defense).

$$Plant\ Replacement\ Value = Facility\ Quantity * Replacement\ Unit\ Cost * Area\ Cost\ Factor * Historical\ Records\ Adjustment * Planning\ and\ Design\ Factor * Supervision\ Inspection\ and\ Overhead\ Factor * Contingency\ factor \quad (3)$$

Plant Replacement Value equation shown on pg. 8 of UFC 3-701-01.

For conventional construction, UFC 3-701-01 was also used to estimate the annual maintenance and repair costs throughout the life of the hangar. The UFC combines these estimates into one unit cost, known as the sustainment unit cost, which includes preventative maintenance, routine repairs, and major overhaul costs throughout the lifespan of the facility. The resulting unit cost will be further adjusted for the location and escalation rates. For fabric construction, once averages were computed for construction, maintenance, and major overhaul costs, these were then multiplied by the same factors required by UFC 3-701-01. UFC 1-200-02 requires that LCC analyses are performed on a 40-year period of study. The two options will be input into BLCC and the net present value of each option after 40 years will be output and compared.

IV. Analysis and Results

Chapter Overview

This chapter provides the results generated from the different avenues of inquiry into the topic of fabric construction. Results will be shown for the three primary methods of research: the qualitative case study, computer-based finite element analysis, and the LCCA comparison of conventional to steel framed fabric aircraft hangars.

Results of Case Study

The following is a compilation of the common themes that were recorded in response to each question used throughout the case study interviews. First, it is important that description of participant is given to provide context to their response. The participants can be categorized as shown in Table 5 below according to the categories discussed in the previous chapter.

Participant	**Occupational Category**
A	Facility Manager/Owner
B	Facility Manager/Owner
C	Facility Manager/Owner
D	Contractor/Manufacturer
E	Contractor/Manufacturer
F	Contractor/Manufacturer
G	Contractor/Manufacturer
H	USAF PM/AFCEC Staff
I	USAF PM/AFCEC Staff
J	USAF PM/AFCEC Staff
K	USAF PM/AFCEC Staff

Table 5. Categorization of participants

Within these categories each of the participants distinguish themselves, and consequently, their responses by their unique experiences and positions within each category. For example, participants A, B, and C all are facility managers or owners of permanently constructed steel framed fabric hangars, but participants B and C have hangars located on civilian airports, and A's hangar supports military aircraft. Walk-throughs were performed of each of these hangars. Each hangars' design will also impact the type of responses seen below. Hangar A was built in 2006, in Oklahoma City, OK, with a fabric membrane that is tensioned over the entire structure. Hangar B, built in Atlanta, GA, has a full membrane as well, but has a horizontal sliding metal door, which is a unique feature among the hangars. Hangar C, built in Rockford, IL, is actually two side by side hangars with steel side walls from foundation to roof and an insulated fabric membrane that clads the roof. Figures 4 through 6 show photographs taken at each of these walk-throughs for further clarification.

Figure 4 Photos taken at Hangar A

Figure 5 Photos taken at Hangar B

Figure 4 Photos taken at Hangar C

In addition to differences evident within the facility manager category, the contractor category has its own idiosyncrasies that need addressing. Firstly, participant G is unique among the four. They are the only participant that does not work for a company that manufactures fabric clad hangars. Participant G has no experience with fabric construction, but offers a perspective from a builder of conventional hangars. Participants E and F are both employed by companies that manufacture, design, construct, and maintain fabric hangars. Participant D works for a vertical lift fabric door (VLFD) company that manufacturers, designs, installs, and maintains the product in-house.

Lastly, there is not a vast difference between the USAF PM/AFCEC staff participants beyond what might be inferred from the category name. Participants H and K have managed USAF hangar construction projects at varying levels of complexity and experience. Participant H has not managed any projects with fabric construction, but K has in a deployed environment. Both participants I and J are AFCEC staff members with varying levels of experience with the topic of hangar construction and fabric construction.

The results of the eleven interviews will be shown below. Responses shown below are a synopsis of responses to each question. These responses are further summarized in tables following each group of questions (i.e. General, Design, Construction, Maintenance, and Operation) into themes that emerged from each category of participants. More detailed descriptions of responses for individual questions are available in Appendix D. The results of constant comparison analysis between participant categorizes is presented in a narrative following the last set of responses.

General Questions

The following are general questions that were given to most participants, independent of category.

Question	**Facility Managers/ Owners**	**Contractors/ Manufacturers**	**USAF PM/ AFCEC staff**
1. *What do you about like about the structure? (Fabric Construction)*	• Transparency • Appearance • Faster construction	• Faster construction • Flexibility of design/modification • light weight • Ease of maintenance • Transparency • Long lifespan	• Faster construction • Flexibility of design/modification
Conventional	N/A	• Easy design	N/A
2. *Would you use the same method of construction again? (Fabric)*	• YES, because: • Low cost • Short timeline • If climate allows	N/A	N/A
Conventional	N/A	N/A	• Hesitant about fabric: • Fragility • Lack of information • Inexperienced contractors
3. *What to change about fabric construction?*	• Add insulation	• Improve appearance	N/A
4. *Why was type of construction chosen? (Fabric)*	• Budget limitations • Low RF impact • Short construction timeline	N/A	N/A
Conventional	N/A	• Long history of success • Insulation	• Low LCC
5. *Why is the USAF interested in fabric construction?*	N/A	N/A	• New msn bed-downs • Potential LCC savings
6. *Why the need for alternatives to conventional?*	N/A	N/A	• Large relative cost of hangar construction in bed-down process
7. *Is the USAF hesitant about using fabric construction? Why?*	N/A	N/A	• Yes: • Environmental limitations • Lack of information • Uncertainty of maintenance reqs
8. *What are some perceived advantages/disadvantages of fabric construction?*	N/A	N/A	• Lighter weight • Daylighting = sustainability • Higher O&M costs • Vulnerability to projectiles

Table 6. Summary of responses to General questions

Design Questions

Questions 9 through 14 were directed at the Contractor/Manufacturer category with overlap on some questions with other categories.

Question	**Facility Managers/ Owners**	**Contractors/ Manufacturers**	**USAF PM/ AFCEC staff**
9. *Are there limitations due to the environment? (Fabric)*	• Cold is a concern for non-insulated • Not vulnerable to wind damage	• No: • Works in high winds • Hot temps • Cold temps • Insulation available at a cost	N/A
Conventional	• Steel hangars damaged in high wind events	N/A	N/A
10. *What experience did the firm have in design of fabric structures?*	N/A	• Started in 1967 • Has worked in US since '83	N/A
11. *How the contractor was selected, and were there many options?*	• Limited options in 2006 • Selected by a P4 bid review team	• Subcontractors hired by a GC • Plenty of direct competition	N/A
12. *What are the common mistakes in design? (Fabric)*	N/A	• Uneducated bid review teams • Fooled by contractors with faulty designs • No PE stamp • Significant amount of work from correction of faulty work	• Owner initially signed up for burdensome warranty
13. *What type of fabric was chosen? Why?*	• PVC/PES: • Low LCC	• PVC/PES: • PTFE/Glass too expensive for marginal increase in lifespan • Constructability	N/A
14. *What design changes were required by AF requirements? (Fabric)*	N/A	• Company goes above and beyond USG reqs	• Has had trouble obtaining calculations
Conventional	N/A	• Low occupancy for AT/FP • Fall arresting system requirements	N/A

Table 7. Summary of Design question responses

Construction Questions

Questions 15 through 21 were again directed at the Contractor/Manufacturer category with overlapping input from the other categories.

Question	**Facility Managers/ Owners**	**Contractors/ Manufacturers**	**USAF PM/ AFCEC staff**
15. Did difficulties arise during construction? If yes, what? (Fabric)	• Yes: • Cold weather delayed PCC	• Wind delays on fabric install • Site restrictions	N/A
Conventional	N/A	• Low bidders • FAA Waiver • USG increases cost of construction	N/A
16. How do fabric hangars differ, if at all, from conventional in project execution?	• Quicker construction periods • Membrane is assembled quickly in sections over frame	• Agreed on process • Can avoid roof work sometimes • High winds can delay membrane install.	• Perceived that fabric construction is quicker
17. What are common sources for delay? (Fabric)	• Sub not used to size of structure • Difficulty with HF welds	N/A	N/A
18. Does weather affect fabric hangar construction differently? If so, how?	• High winds delay membrane installation	• High winds delay membrane installation • Extreme cold requires careful tensioning	N/A
19. Does QA/QC differ when constructing fabric hangars vs conventional? If so, how?	• No major differences	• Different testing standards and procedures • Separate QA/QC for fabric and steel components	• Difficulty in obtaining material properties • Difficulty in getting correct design calcs
20. How many companies were available? (Fabric)	N/A	• Between 6-10 close competitors	• Relatively smaller pool of contractors • Not low enough to need sole source
Conventional	N/A	• No issues with getting competition unless remote location	N/A
21. What standards hold contractors accountable?	N/A	• UFGS for VLFDs has been helpful	N/A

Table 8. Summary of Construction question responses

Maintenance Questions

Questions 22 through 27 were directed at the Facility Manager/Owner category with overlap from other categories where relevant.

Question	**Facility Managers/ Owners**	**Contractors/ Manufacturers**	**USAF PM/ AFCEC staff**
22. Who is in charge of maintenance? (Fabric)	• Maintenance service contracted through installing manufacturer	• Contracted PM • user-performed	• In-house maintenance was limited • Needed contracted PM • AFI mandated maintenance plan for sunshades
Conventional	N/A	• User-performed	• User-performed
23. Are there typical warranty calls? (Fabric)	• Patch repair due to metal debris	• Initial tensioning as membrane acclimates	• Structural failures from poor construction
Conventional	N/A	• Leaks in cladding	N/A
24. What type of warranty comes with the facility? (Fabric)	• Initial warranty replaced with service contract	• 20-yr available with maintenance contract and inspections	N/A
25. How does the maintenance of this facility differ, if at all, from a conventional hangar?	• Manufacturer provides patch repair kits	• Patch tears • Leaks • Re-tension fabric and cables • Cleaning if desired • Annual fabric wear inspection	• Patch repairs performed by base personnel • Perceived technically easy maintenance, but hesitant about longevity
26. Are there different maintenance concerns for fabric hangars than what is typical of a conventional hangar, If so, what?	• Small patch repairs • Birds are attracted to daylighting • Low maint.	• Replacing membrane similar to repainting steel hangar	N/A
27. How much downtime has maintenance caused?	• 30 Days to replace membrane	• Minimal • Only impacted if repairs are large	• Patches did not cause downtime

Table 9. Summary of Maintenance question responses

Facility Operation Questions

Questions 28 through 30 were directed at the Facility Manager/Owner category with overlap from the other categories where relevant.

Question	**Facility Managers/ Owners**	**Contractors/ Manufacturers**	**USAF PM/ AFCEC staff**
28. What level of training is required to adequately manage the facility? (Fabric)	• Fire department procedural adjustments	• Need to ID tears in fabric and inspect for areas that need re-tensioning	N/A
Conventional	N/A	• Biggest concern is correct O&M of fire suppression systems	• Operation of doors in high winds
29. Are there changes to the way users operate due to fabric construction? If so, what?	• Daylighting improves productivity/morale	N/A	• Impacted because missions had to relocate
30. Are there limitations to operations in fabric hangars that are not typical of conventional?	N/A	• Users need to be aware of vulnerability to puncture	N/A

Table 10. Summary of Operation question responses

Summary of Responses

The responses to questions 5 through 8 provide an important context for the responses in the case study interviews. These responses show that in light of current efforts to bed-down new missions across the USAF, there needs to be an effort to minimize life-cycle costs throughout the process. Given that aircraft hangars account for a large amount of costs associated with mission bed-down, it was perceived that large savings could be generated in this area. USAF civil engineers have looked to fabric construction as a potential solution, but are hesitant to move forward due to a lack of information on construction costs, maintenance requirements, and ability to meet needs of USAF missions. From cursory research, USAF civil engineers predict that this type of construction has added benefits such as lighter weight materials and natural lighting due to fabric translucency, and therefore lower construction costs.

Common advantages of fabric construction are its speed of construction, the adaptability of the structure to location and changing user requirements, and natural lighting added by the membrane's translucency. In contrast, the consistent advantage of using conventional hangars is that they are easy to design according to DoD requirements. Facility managers would all use fabric construction again for a hangar project because of its relative low cost and short construction timeline. The conventional construction contractor and USAF staff members continue to use conventional methods, because of its long history of success and predictability in both design and construction.

It was apparent that facility managers were concerned with using fabric construction in cold climates due to the lack of insulation. However, many of the manufacturers/contractors claim that their structures can be designed for any climate to include options for adding insulation. Despite the many potential advantages of fabric construction, there are common mistakes, mainly attributed to poor oversight in the design process. These structures still have to meet building code requirements for permanent construction. Therefore, designs must be able to show technical understanding of how fabric membranes behave, and be designed to functionally operate for lifespans typical of permanent structures. It was consistently shown that PVC/PES is the chosen material for permanent construction given its relative long lifespan and low cost compared to other membrane materials.

The stated difficulties in construction from contractors and facility managers were not unique for any construction project. Facility managers confirmed USAF predictions that construction timelines are shorter for fabric hangars. Participants described a similar process of construction where the steel structure is erected, the membrane is fastened in panel sections, and then tensioned. During construction, a common concern is that fabric membranes cannot be installed in high winds. Future project managers need to be aware that fabric membranes are subject to unique material testing standards that differ from that of conventional construction. As for contractor availability, conventional hangars typically see an unlimited pool of contractors. While fabric construction has a smaller set of contractors competing, this typically does not warrant the need for sole source selection on hangar projects.

Based on responses from all categories, it is most practical to establish a service contract with the installer for preventative maintenance in order to preserve the membrane's warranty. Common repairs performed under the warranty of fabric hangars include patch repairs and tensioning due to membrane acclimation to the climate. In comparison, the most common warranty work on conventional hangars is leak repairs. Contractors have 20-year warranties available that include preventative maintenance and annual inspections with the installer. Typical maintenance tasks on fabric hangars include patches performed with the use of contractor-provided kits, re-tensioning of fabric and cables, and cleaning the membrane. Maintenance only impacts the user's operation if there is a major repair such as a panel replacement or complete membrane replacement.

The only significant difference in facility management training for fabric hangars was the adjustments that the fire department had to make to their procedures for the new type of structure. There were no significant changes to the way users operate within the hangar besides the added benefit of daylighting.

Results of Structural Analysis

The following are the results of the comparative structural analysis performed in ABAQUS/CAE © finite element software. Initially, design loads to be applied to both structures were calculated according to ASCE 7-10. Table 7 summarizes these calculations and presents the unfactored loads that were used in each model. Tables providing further detail on these calculations can be found in Appendix B.

	Conventional	**Fabric**
Roof Dead (psf)	**12**	**5.25**
Roof Live (psf)	20	20
Roof Wind, (-GCp)		
Zone 1 (psf)	-66.9	-66.9
Zone 2 (psf)	-97.74	-97.74
Zone 3 (psf)	-128.6	-128.6
Walls Wind, (-GCp)		
Windward (psf)	50.34	50.34
Leeward (psf)	-49.72	-49.72
Horizontal Seismic (kips)	**10.8**	**6.9**

Table 11. Summary of calculated unfactored design loads.

Continuing with Allowable Stress Design (ASD) criteria, as prescribed by ASCE 7-10, equations 4 and 5 were the controlling load conditions for the two models.

$$D + 0.6 * W \quad (4)$$

$$D + 0.75 * (0.6 * W) + 0.75 * L_r \quad (5)$$

Where D is taken to be the dead load, W is the wind load, and Lr is the roof live load. Using the dimensions and steel member specifications from the Tinker AFB hangar design, the structural frame was assembled in Abaqus. Figure 5 shows a rendering of the assembled conventional model. This gives a good perspective for how simplified the model is compared to the design hangar. The model excludes the hangar door and pocket frame as well as several bays. However, with those exclusions, in the two frame bays shown, the model includes most of the structural elements from the design.

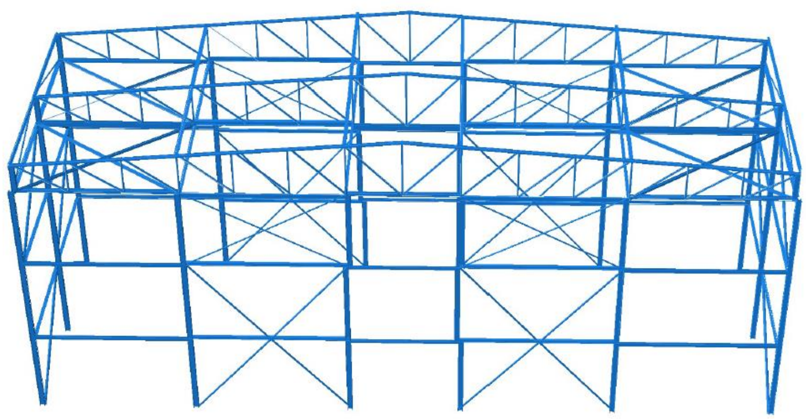


Figure 5. Assembled conventional model

The conventional model assumes a steel deck and standing seam metal roof cladding as per the design documents. However, the cladding itself was not modelled in Abaqus. The dead load corresponding to the decking was superimposed onto the frame and applied as point loads. The resulting increased dead load which was imposed on the frame is reflected in Table 7. The fabric model uses the same assembly shown in Figure 5 with the addition of membrane panels. Figure 6 shows the assembly prepared for load cases in which the wind load was applied in the x-direction.

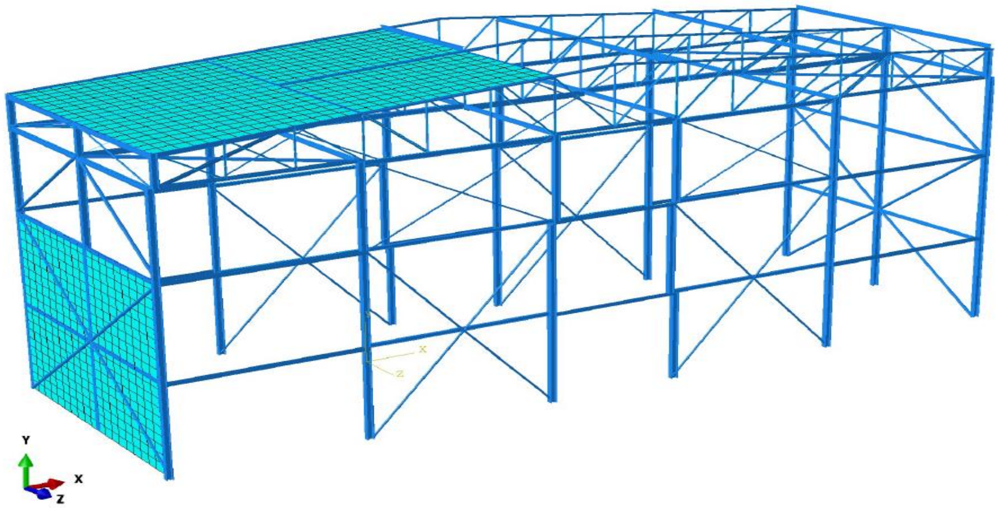


Figure 6. Fabric model assembly.

The fabric model does not include cladding for the entire structure because Abaqus could not converge on a solution for that complex of a model. The model is simplified to only include cladding in the areas with the highest applied load and largest spans.

For both models, fixed foundation connections were assumed according to the type of connections shown in the design documents. These conditions are input to Abaqus as boundary conditions as shown in Figure 7.

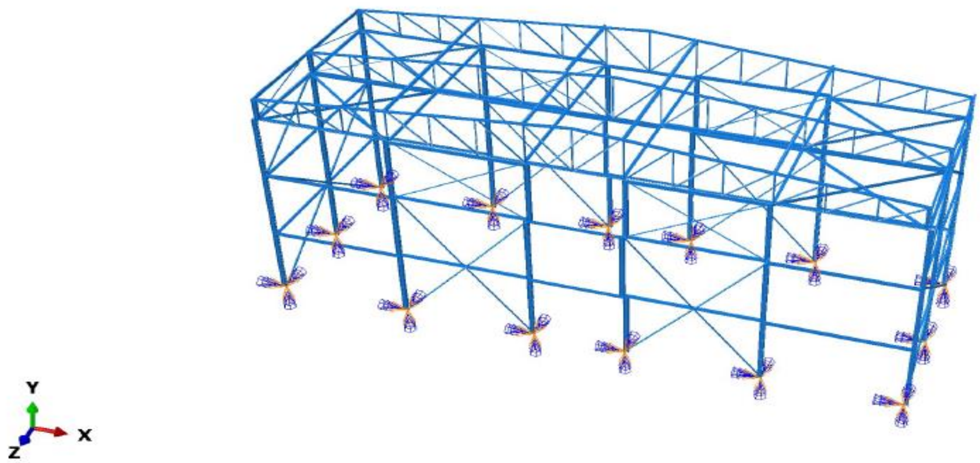


Figure 7. Boundary connections used in both models.

Loading for the conventional model was applied for four load cases. Load cases 1 and 2 both based on equation 5 with the wind load applied in the x-direction and z-direction respectively. Similarly, load cases 3 and 4 are based on equation 4 while varying the direction in which the wind load is applied. Figure 8 and 9 show load cases that apply the wind load in the z and x-direction respectively.

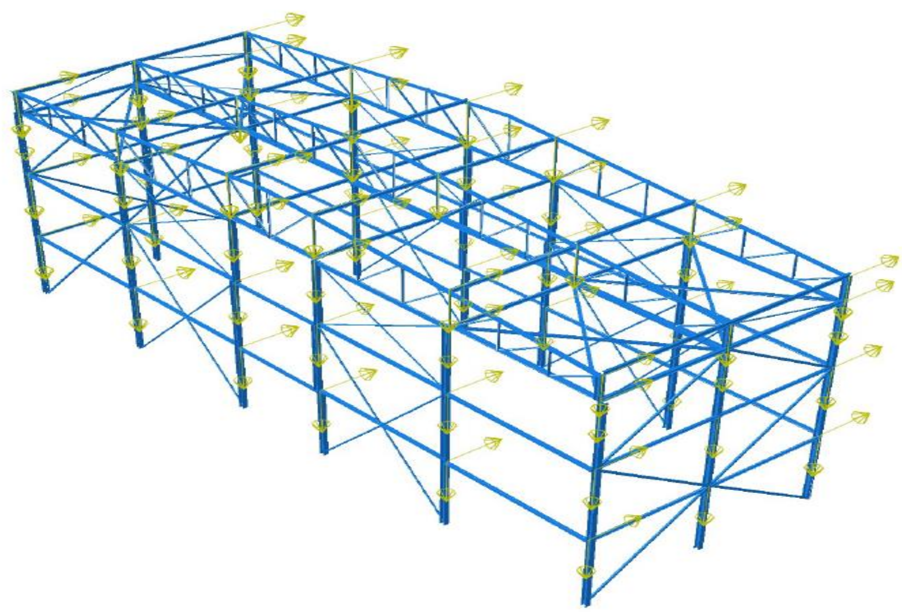


Figure 8. Loading in the conventional model for cases with the wind load applied in the z-direction.

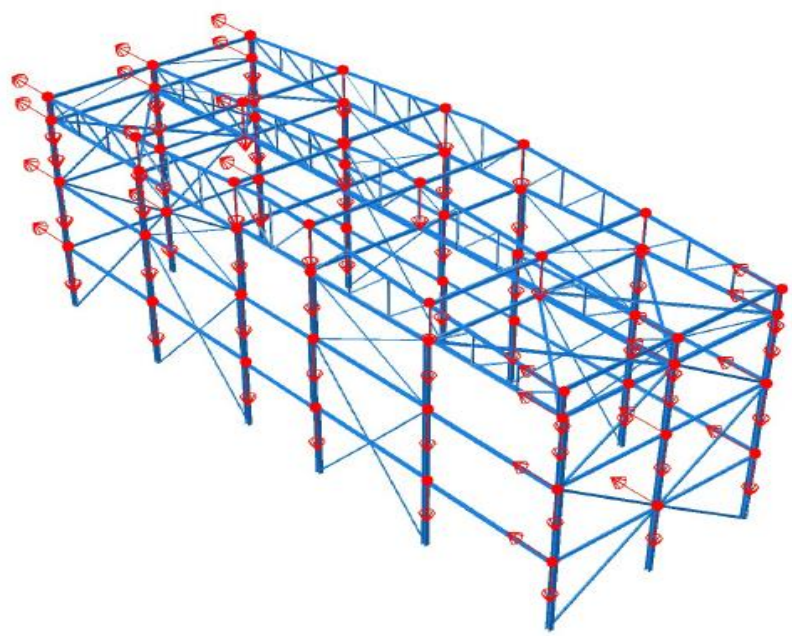


Figure 9. Loading in the conventional model for cases with the wind load applied in the z-direction.

The fabric model was loaded with similar load cases to the conventional. However, in the fabric model, the loads were represented as distributed loads over the fabric panels that were selected for that particular load case. As was done with the conventional model, loading in the x and z-direction are shown below in Figures 10 and 11. Additionally, the Abaqus CAE user guide recommends adding a prestress condition to membrane elements prior to loading to avoid computation issues associated with instability. Typical prestress for PTFE/Glass membranes noted in the literature is 6 kN/m (412 lb. /in), so this was applied to the fabric panels in both in-plane directions (Task Committee on Tensioned Fabric Structures).

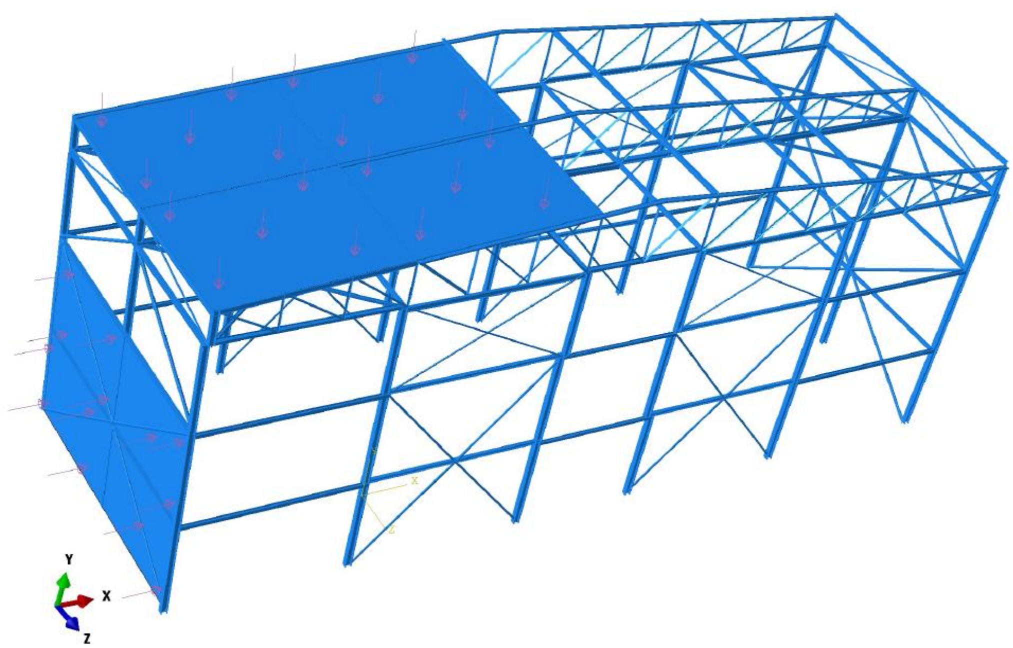


Figure 10. Loading in the fabric model for cases with the wind load applied in the x-direction.

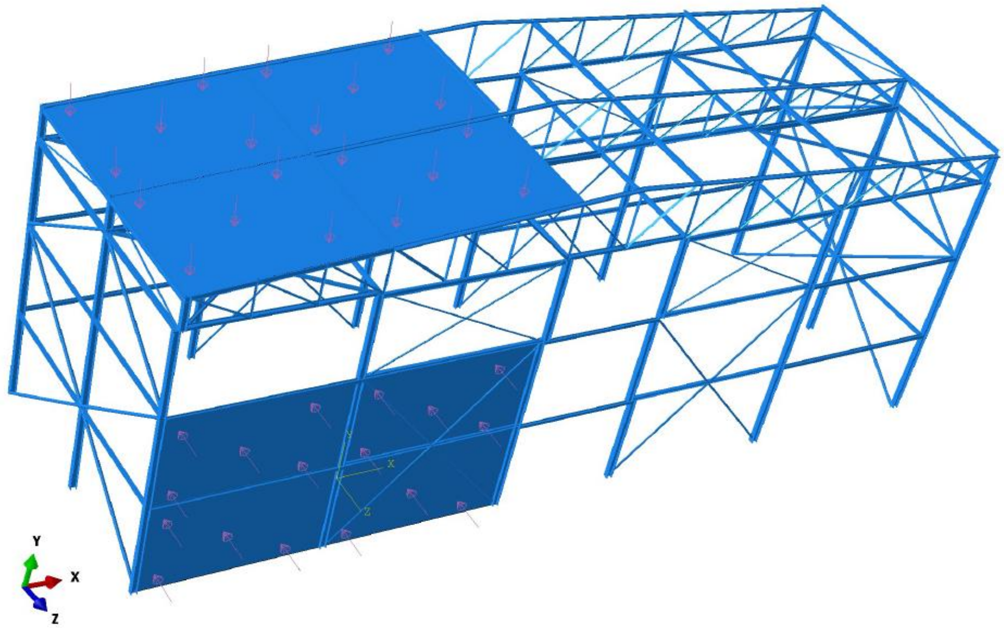


Figure 11. Loading in the fabric model for cases with the wind load applied in the z-direction.

Another difference in the fabric load cases is that the entire model is not loaded. This was done again to simplify the analysis performed in Abaqus. This was also done because the steel frame was already analyzed in the conventional model with higher distributed loading. Therefore, it was assumed sufficient to leave analysis of the frame out of the fabric model. In the fabric model, the item of concern is performance of the membrane cladding under the various load cases.

A summary of the worst stress and deflection conditions for both models is shown below in Table 8. The figures below provide further clarification for the individual worst cases for each model. Figure 12 represents the load case which resulted in the highest deflection on a roof member, and therefore the controlling load case for the IBC deflection limit of L/180 for roof members not supporting a ceiling (International Code Council).

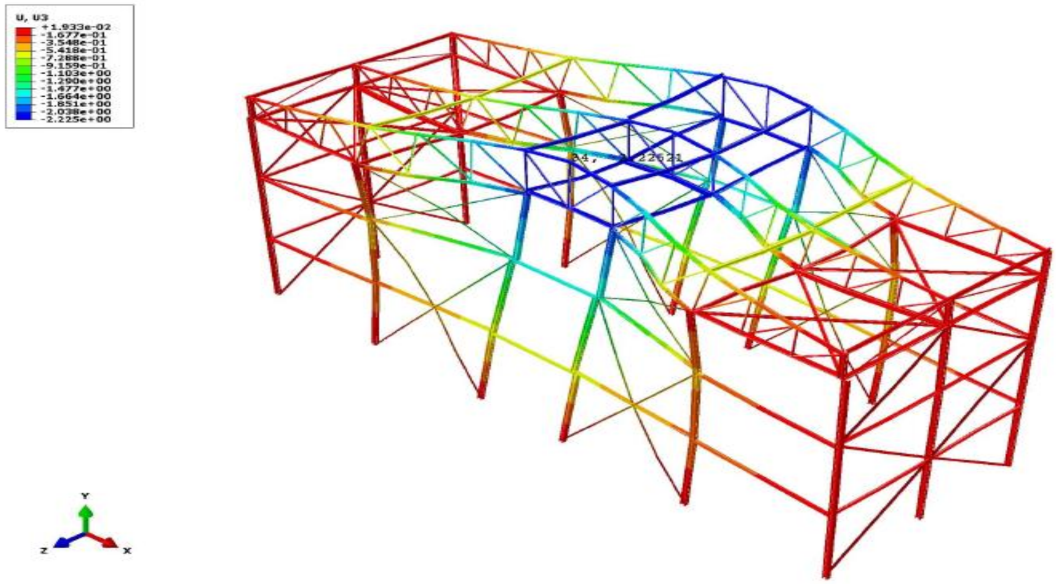


Figure 12. Conventional model loaded with 0.42*Wind Load. Roof member with the max deflection is labeled.

The W14X109 labeled in the figure far exceeds the IBC limit 1.86in assuming a length of 28 ft. (the distance between supporting girders at the ends of this beam).

The drift limit for the conventional model was calculated using equation 6 derived from Table 12.12-1 of ASCE 7-10.

$$\Delta_a = 0.02 * h_{xx} \tag{6}$$

Where Δ_a is the allowable drift, and h_{xx} is the elevation at the peak of the structure's roof. Figure 13 shows drift calculated at the roof center of mass for Load Case 4.

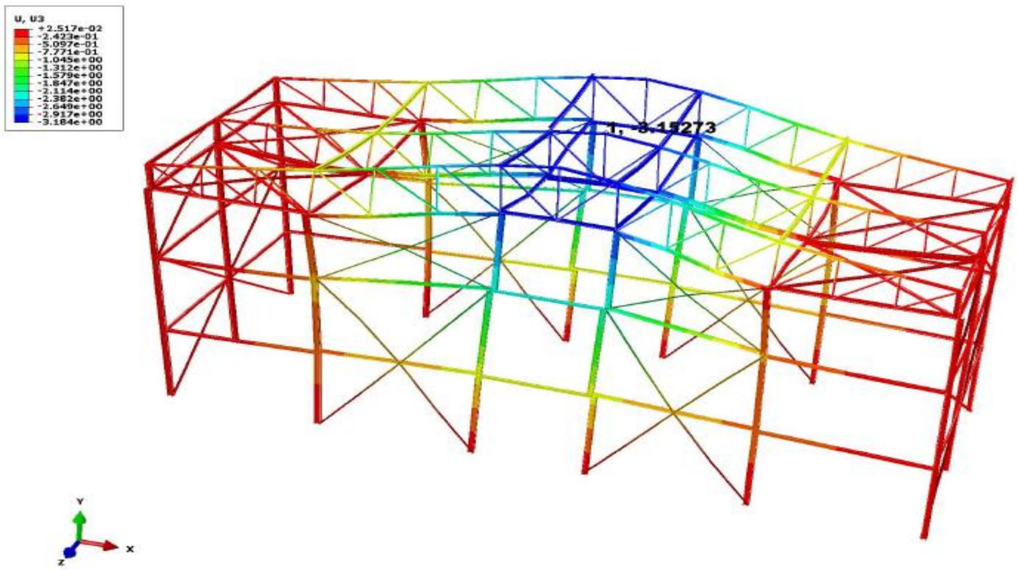


Figure 13. Conventional model loaded with Load Case 4. The roof center of mass is labeled, and the displacement in the z-direction is shown.

As shown in Table 8, the calculated drift far exceeds the limit imposed by ASCE 7-10.

Figures 14 and 15 show the highest stressed beam and column members of the analyses performed on all load cases for the conventional model.

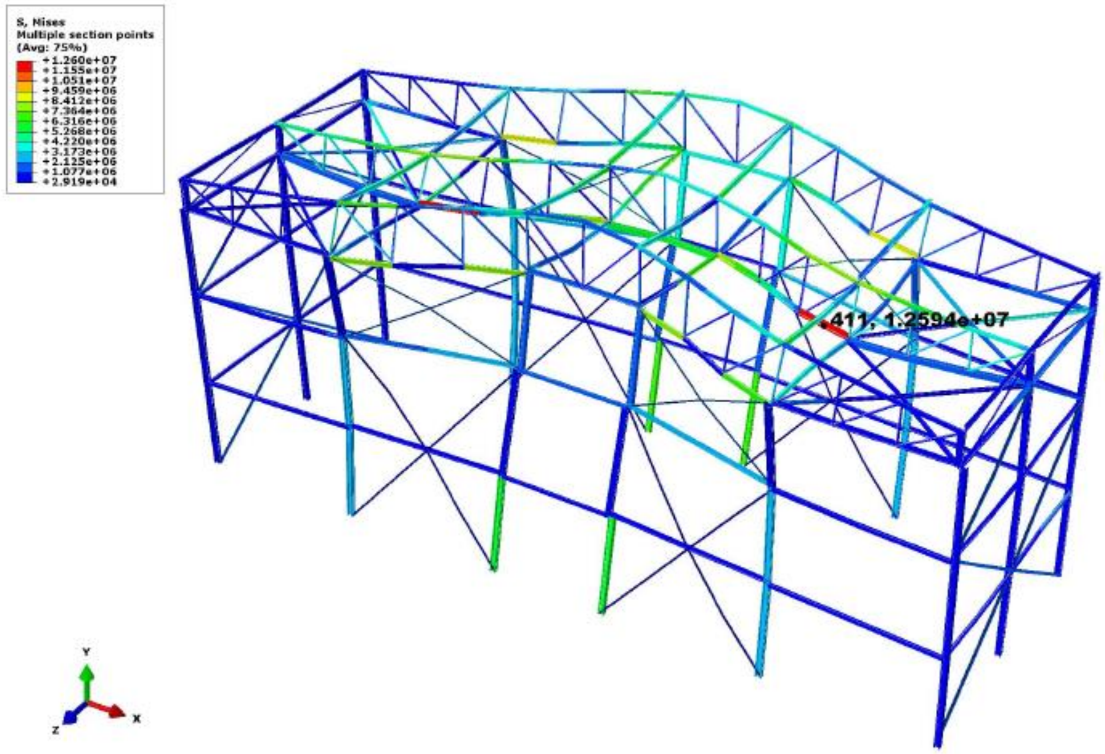


Figure 14. Conventional model loaded with Load Case 4, showing the highest stressed beam member.

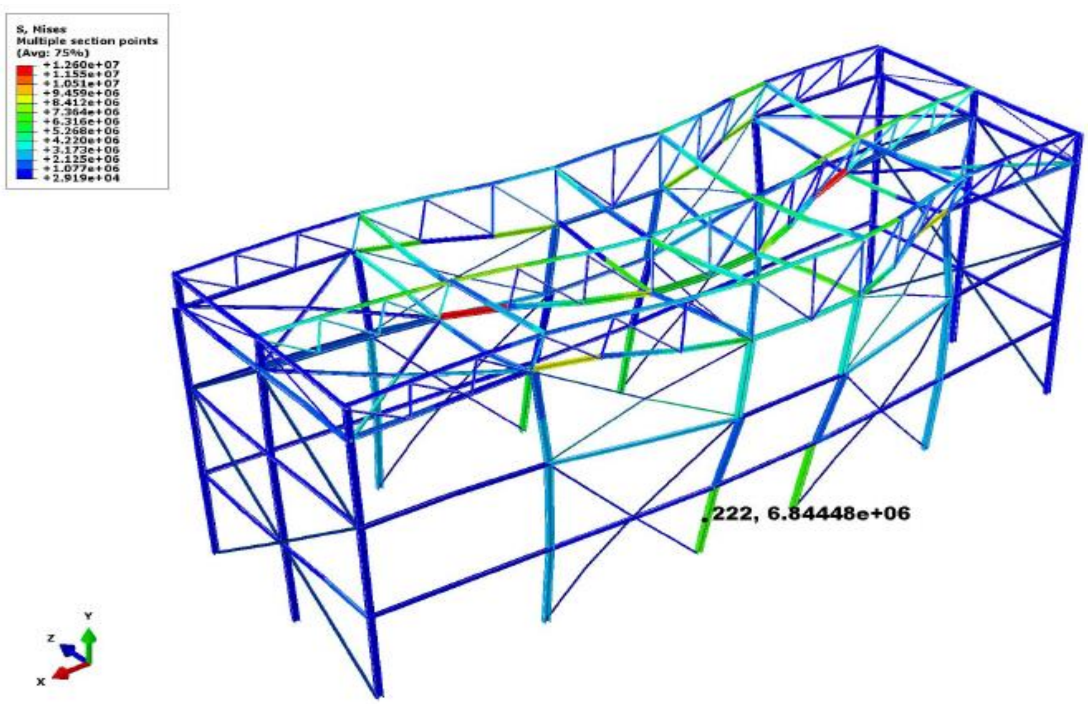


Figure 15. Conventional model loaded with Load Case 4, showing the highest stressed column member

Figure 16 shows the highest stressed membrane panel of all load cases conducted on the fabric model. The notes on Figure 16 show that the step time for the analysis only reached 0.103sec. This is indicates that the model was not loaded completely, since the total step time is one second. The below graph in Figure 17 shows a plot of stress at the element highlighted in Figure 16 versus analytical increments.

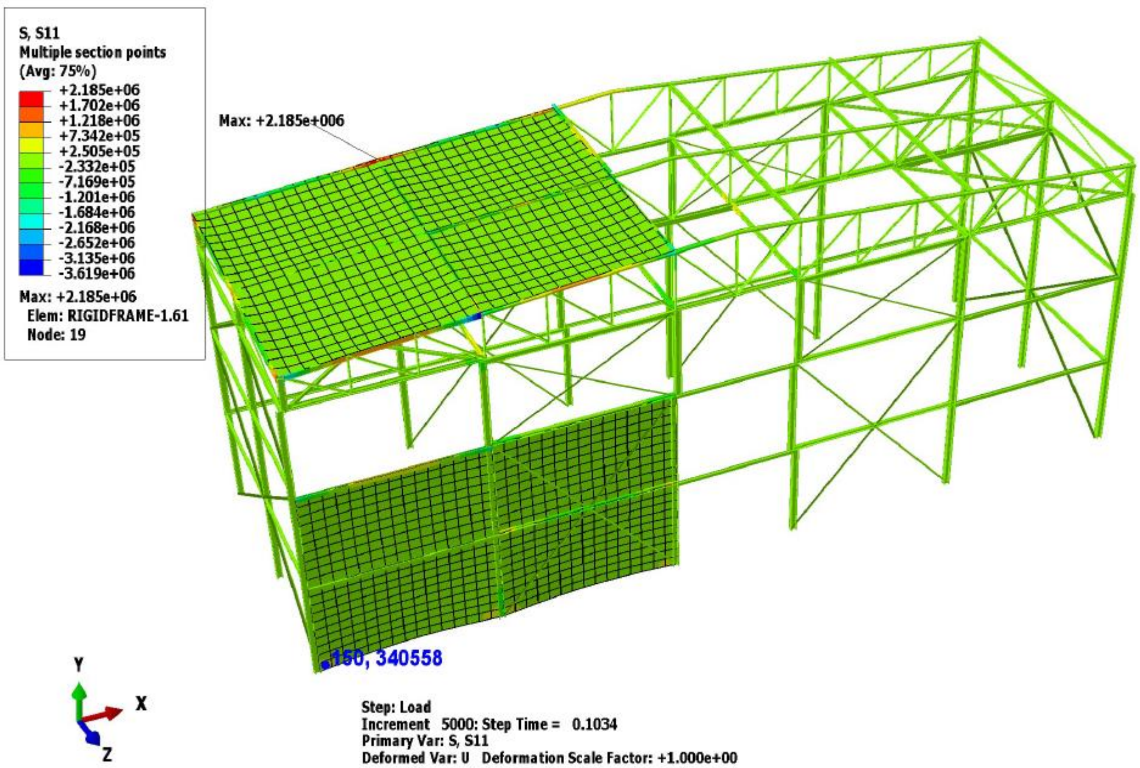


Figure 16. Max in-plane stress for fabric model using Load Case 4.

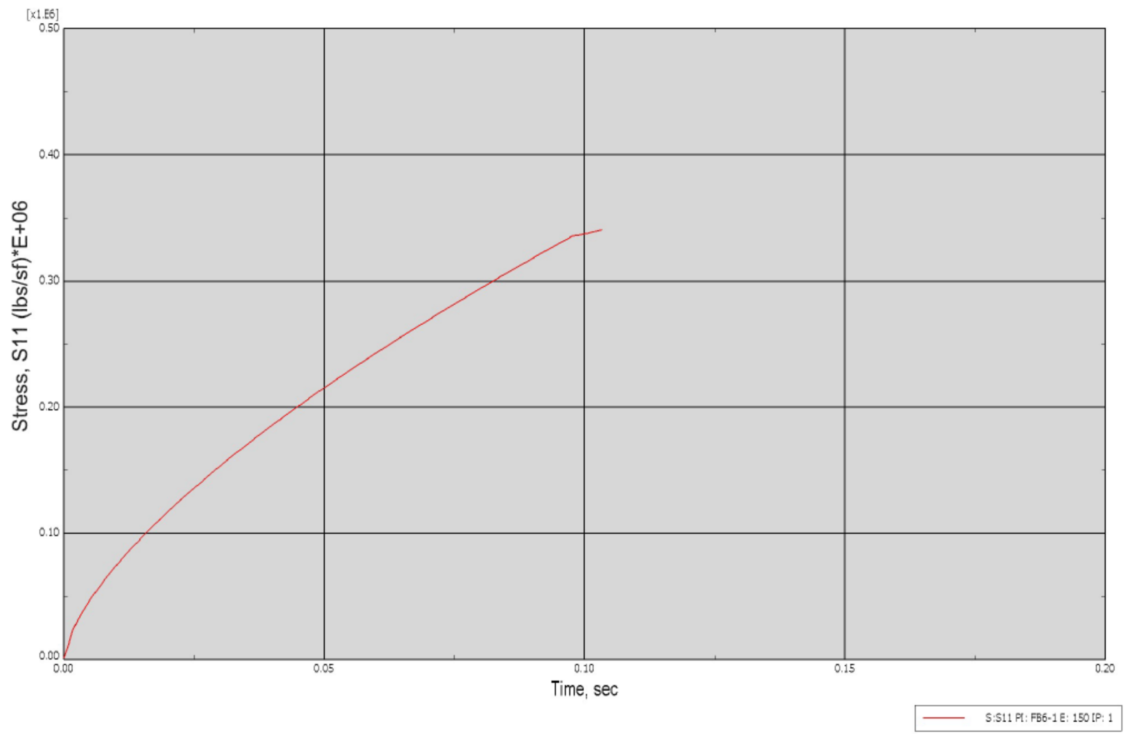


Figure 17. Graphical output from Abaqus of S11 vs Time at max stress element in fabric model.

From this graph it is apparent that the rate of increase in stress gradually slows over the duration of analysis. This trend is extrapolated in Figure 18 that applies linear trend lines to the data obtained from Figure 17.

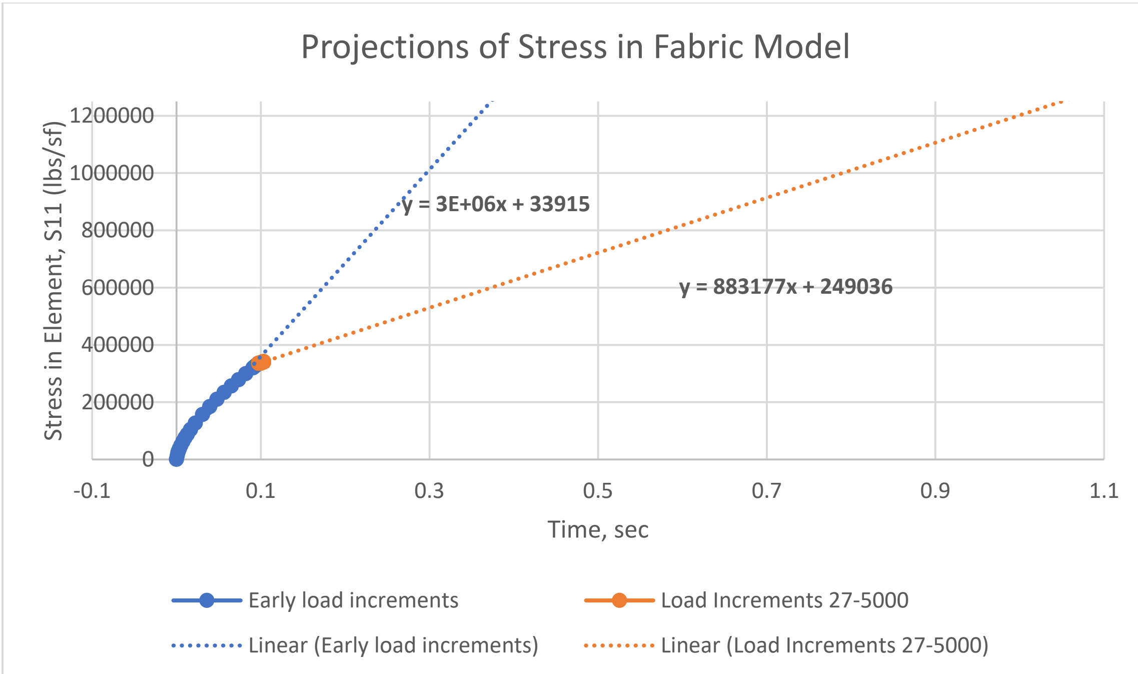


Figure 18. Extrapolation of data obtained from fabric analysis

The trend line shown in blue represents data from increments 1-26. The other trend line represents data from increments 27-5000 of the analysis. At this stage in the analysis, increase in stress is marginal and progression through load cycle time slows. Given the trends shown Figure 18, it is likely that stress will continue to increase either along or below the second trend line if the analysis was continued to its end. Therefore, the value of stress at one second will be conservatively estimated based on the linear equation shown for the second trend line. This value is shown in Table 8.

Another check performed on the Abaqus results was done analytically. The Task Committee on Tensile Fabric Structures (TC on TFS) recommends the following for estimating tensile force in a membrane given an applied pressure:

> The curvature of most surfaces can be reasonably approximated by circular arcs over a finite distance. This simplifying assumption can be used with the structural characteristics of membranes: no compression, bending or shear, balanced tension forces and minimal surface area to develop a reasonable analysis. pg. 66 of *Tensile Fabric Structures*

The tensile force in the membrane was thus estimated using simple linear analysis. Appendix B provides more details on the calculations used. The estimate for stress in the highest loaded membrane panel is shown in Table 8. Note that, as the TC on TFS explains, this estimate does not account for nonlinear increases in tensile load capacity of the membrane as it deflects and is therefore a conservative estimate of stress in the membrane. An initial sag of the membrane is assumed as the deflection produced by Abaqus, as shown in Figure 19, and the estimate proceeds from there.

Figure 19 shows the maximum deflection of a membrane panel in the fabric model.

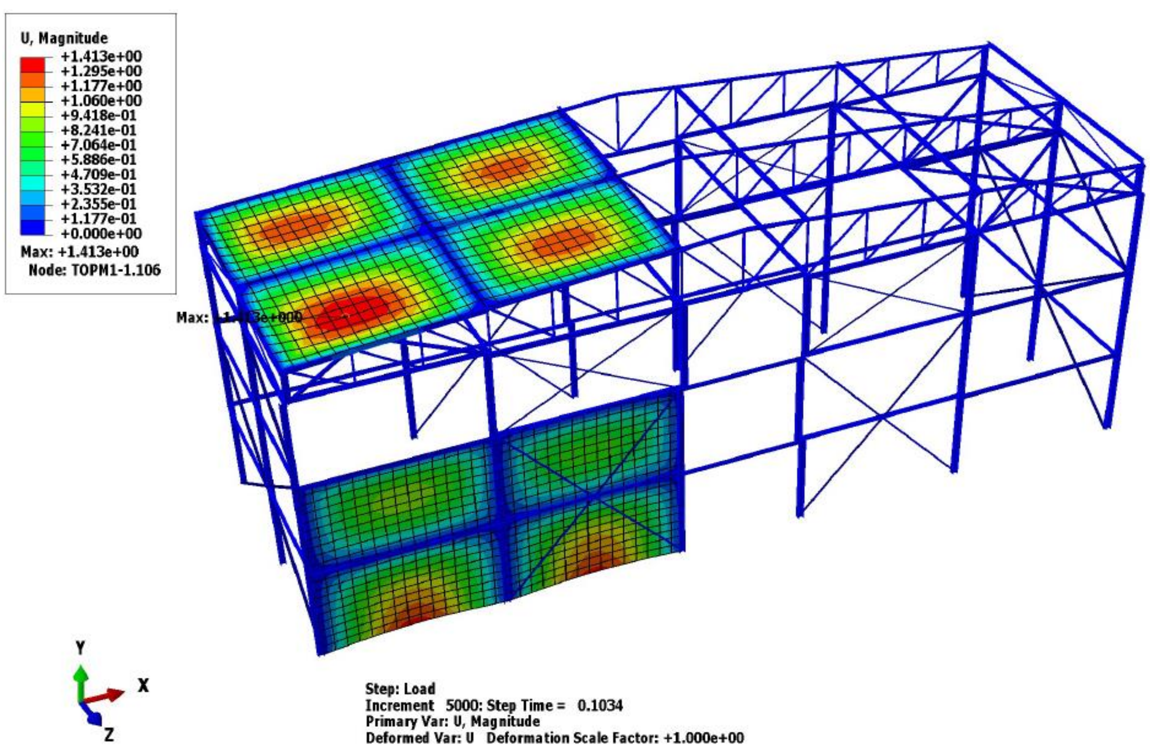


Figure 19. Max deflection in fabric model using Load Case 4.

Per the IBC section 3102, there is no explicit limit on deflection for fabric membranes, the deflection is just worth noting for comparison to the conventional model (International Code Council). In Figure 19, it is apparent that the steel frame gains significant stability from the attached membrane cladding.

Conventional				Fabric		
	Demand	*Capacity*	*D/C*	*Demand*	*Capacity*	*D/C*
Beam (W14X109)	87500psi	50000psi	1.75			
Column (W14X233)	47528psi	50000psi	0.95			
Diagonal (2L4X4X0.25)	37465psi	36000psi	1.04			
Drift	37.8in	20.5in	1.84			
Exterior Wall Framing, Live Load Deflection	0.37in	5.72in	0.06			
Roof LL Deflection	2.38in	1.40in	1.70			
Roof 0.42W Deflection	26.76in	1.87in	14.34			
Roof D+L Deflection	4.28in	2.72in	1.58			
Decking Max Load from Tinker AFB Design	64psf	65psf	**0.98**			
Membrane (Sheerfill I ®) Warp Direction				2362psi	28472psi	0.08
Membrane Warp Direction Linear Extrapolation				7863psi	28472psi	0.28
Membrane Warp Direction Analytical Approximation				11300psi	28472	**0.40**
Membrane Fill Direction				1541psi	26389psi	0.06
Membrane Deflection				N/A	16.75in	N/A

Table 12. Summary of factors of safety for each model

Considering the results from the conventional model, the high deflections and stresses may be attributed to a change in dimensions of the overall structure causing instability due to a rectangular shape. This would definitely explain the deflection due to wind loading in the z-direction, which is the long side of the structure. The primary cause of instability is likely the lack of cladding and the associated stability in the conventional model.

The controlling safety factor from the fabric model comes from a comparison of in-plane stress to the manufacturer provided warp direction fabric breaking strength (see Appendix C for material specifications). With an estimate demand-to-capacity ratio of 0.28, the factor of safety for the fabric used in this analysis is **2.52**. This compares well to the factor of safety of **1.02** for the decking used in the Tinker AFB design.

Results of Life Cycle Cost Analysis

The following are the results from the LCC comparison performed with the aid of the Building Life-cycle Cost 5 (BLCC 5) program. Table 9 summarizes the inputs into the program. A more detailed listing of data used to obtain these inputs is available in Appendix A.

Input	Base Case: Conventional Steel Hangar	Alternative: Steel Framed Fabric Hangar
Study period	40 years	
Discount Rate	2.8%	
Location	Oklahoma	
Initial Cost	$17,638,503.00	$5,728,052.00
Average Annual Maintenance and Repair (M&R) Cost	$20,102.00	$11,895.00
Re-Roofing Cost at 20 years	$0.00	$271,375.00

Table 13. Summary of Inputs to BLCC 5

Table 13 and 14 summarize the results produced by BLCC 5. Table 10 summarizes results from Life-Cycle Costs (LCC) of both types of construction. BLCC 5 conducts the analysis by computing the present value of initial costs, annual maintenance and repair costs, and major overhaul costs of each option. These present values are then totaled as a LCC. BLCC 5 also conducts a similar analysis to obtain an annual LCC.

	Base Case: Conventional Steel Hangar	**Alternative: Steel Framed Fabric Hangar**
Present Value (PV) of Initial Cost	$17,638,503.00	$5,728,052.00
PV of M&R Cost	$681,217.00	$403,103.00
PV of Major Repair and Replacement Costs	$0.00	$235,103.00
PV of Total Life-Cycle Cost	**$18,319,719.00**	**$6,366,257.00**
Annual Cost	**$767,164.00**	**$266,596.00**

Table 14. Summary of Life Cycle Costs

Table 15 takes the data from Table 13 and calculates savings over the 40 year period by choosing the alternative over the base case. By combining the future costs of both construction types, it is apparent that there are minimal savings accrued in the maintenance and repair of steel framed fabric hangars. The majority of savings in LCC clearly is from the initial cost of construction.

	Base Case: Conventional Steel Hangar	Alternative: Steel Framed Fabric Hangar	Savings from Alternative
Initial Investment	$17,638,503.00	$5,728,052.00	$11,910,451.00
Routine Recurring and Non-Recurring M&R Costs	$681,217.00	$403,103.00	$278,114.00
Major Repair and Replacement Costs	$0.00	$235,103.00	-$235,103
Subtotal (for Future Cost Items)	$681,217.00	$638,206.00	**$43,011.00**
Annual Cost	$18,319,719.00	$6,366,257.00	**$11,953,462.00**

Table 15. Summary of Comparative Analysis

V. Conclusions and Recommendations

Chapter Overview

At the outset of this paper, the purpose of research was organized by four decision criterion: research consensus, structural safety, mission functionality, and economic feasibility. These criterion established the framework for investigating whether or not the USAF and DoD should pursue the use of steel framed fabric hangars as an alternative to conventionally constructed permanent aircraft hangars. Research consensus of steel framed fabric hangars drove an exploration into current DoD construction standards, industry building codes, and best practices from the fabric construction industry. Structural safety of steel framed fabric hangars was assessed through finite element analysis (FEA). In case study interviews with facility managers, contractors, and USAF staff members, mission functionality was assessed. Finally, the LCC comparison between the two types of construction strove to test the economic feasibility of investing in the new type of construction.

Research Consensus

It was found that fabric construction does incur more stringent design requirements for fire protection, since materials used are considered Type IIB or V per NFPA 409.

The literature did not provide much detail on tensile fabric membrane performance as a building envelope. However, case study interviews with contractor participants showed that fabric membranes are designed to be water tight and provide a moisture barrier against condensation. The participants also point out that fabric membranes can be designed to include insulation.

Another concern raised during examination of UFC 4-211-01 was the requirement to build hangars with a masonry wall from floor level to 10 feet. The Atlanta and Rockford hangars are successful examples of fabric membrane rooves coupled with solid walls.

Based on the assessment of fabric construction standards, best practices, and results of the case study, it is recommended that fabric membranes follow the same requirement as Vertical Lift Fabric Doors (VLFDs) to be prohibited from use in wind-borne debris regions (Department of Defense).

Structural Analysis

The finite element analysis of the fabric membrane material Sheerfill ®, reinforced that fabric membranes can provide equal, if not more, structural safety in comparison to claddings used on conventional structures.

Case Study Analysis

Table 12 compiles results from both the literature review and case study analysis to summarize the advantages and disadvantages of fabric and conventional construction. This research largely focused on establishing a foundation of information for steel framed fabric hangars. Therefore, much of the literature used and questions asked provided information on fabric construction, but lacked in insights about conventional hangars. It is also assumed that much of the audience is familiar with advantages and disadvantages of conventional hangars, and can therefore draw on past experience and knowledge to improve this comparison.

	Fabric Construction		Conventional Construction	
	Advantages	*Disadvantages*	*Advantages*	*Disadvantages*
General	Natural lighting added by translucent membrane material	More vulnerable to puncture (e.g. flying debris, maintenance equipment impact)	Long history of success	High cost (both construction and life cycle)
	Lower construction and life cycle cost		USAF PMs are relatively informed on design and construction reqs	
	Low impact to radio frequencies			
Design	Significant reduction in structural dead load	Materials are limited to Type IIB and Type V for NFPA fire resistance	Easy to meet UFC requirements	
	Membrane materials are not significantly affected by difference in internal and external temperatures	Technically difficult design. If custom structure, recommend specialty engineer	Not limited by material fire resistance	
	Easily adaptable to user requirements and existing site restrictions			
Construction	Faster construction	High winds delay membrane installation	Relatively large pool of contractors for project	Costly
	Smaller and less equipment required to erect structure	Smaller number of contractors with expertise	Well understood construction procedures	Long construction duration
Maintenance	No impact to operations during maintenance	Lifespans range from 15-30 years	Standing seam metal rooves have a longer lifespan than fabric construction	Many more maintenance concerns for conventional cladding
	User can repair tears in membrane with patch kits provided during installation			Major repairs to cladding can be costly and time consuming
	Significantly fewer maintenance concerns			Some cladding systems (i.e. SSMR) are vulnerable to high wind damage
	Re-roofing is relatively quick and inexpensive			

Table 16. Summary comparison of pros and cons captured from literature review and case study results

As shown in Table 12, there are trade-offs in many of the categories between fabric and conventional construction methods. However, as previously stated in the case study analysis, the USAF is interested in evaluating potential life-cycle cost savings and gained mission bed-down flexibility. With that focus in mind, it is apparent that fabric hangars provide faster execution and a lower LCC than conventional hangars. The key tradeoffs seem to be associated with lack of information and standards on fabric construction. If this type of construction is adopted, there needs to be a commiserate adoption of design and construction standards made available to USAF Project Managers.

Life-Cycle Cost Analysis

The LCC comparison between the two types of construction showed relatively equal costs in maintenance and repair, but significantly lower costs to construct fabric hangars. Therefore, over a life-cycle of 40 years, steel framed fabric hangars are cost effective when compared to conventional hangars.

Conclusion

Throughout this paper, the goal was to answer the following:

- Do steel framed fabric hangars comprehensively meet or exceed the levels of performance that the USAF/DoD requires from conventional hangars?
- What fabric materials meet the needs of USAF permanent construction and are readily available on the construction market?
- Are steel framed fabric hangars as, or more, structurally safe as conventional hangars?
- Are steel framed fabric hangars as, or more, life-cycle cost effective as conventional hangars?
- Are steel framed fabric hangars practical for the USAF?

Through examination of UFC and industry building codes, there are no significant barriers keeping the USAF/DoD from using steel framed fabric hangars in place of conventional hangars for permanent construction. However, supplements to the existing UFC should be made to account for requirements unique to fabric construction. Recommendations for these changes will be made in the following section.

As previously discussed, PVC/PES and PTFE/Glass, are the two leading architectural fabrics readily available in the construction industry today. Given the negligible difference in strength and lifespan, and significant lower cost of PVC/PES, PVC/PES is the more appropriate option for use in USAF/DoD facilities. Additionally, this was further validated from responses in interviews where participants used PVC/PES in their own hangars.

The case study analysis showed consistently that steel framed fabric hangars were constructed quicker and for lower cost than conventional hangars. The interview results describe a substantially shorter list of maintenance line items than was found for conventional hangars. The design of these structures is more technically difficult than conventional structures, which poses a challenge for design review teams unfamiliar with fabric construction standards. If project managers and design review teams are provided guidelines that clarify permanent construction requirements for fabric hangars, then the challenge of a more technical design can be overcome. The interviewed participants confirmed there were no additional impacts to operations resulting from using fabric hangars, in lieu of conventional. Additionally it was found that steel framed fabric hangars are both as structurally safe and life-cycle cost effective as conventional hangars. Given these results, steel framed fabric hangars are practical for the USAF.

Recommendations for Action

This research recommends the USAF implements steel framed fabric hangars as an alternative to conventional construction for new aircraft hangar projects. By investing in this type of construction, the USAF will save considerable costs to the US taxpayer.

Shorter construction delivery times will allow commanders more flexibility in mission bed-down. Lastly, reduced maintenance concerns typical of fabric hangars will lessen the burden on installation facility maintenance personnel.

In order to properly initiate this new type of construction, it is recommended the USAF and DoD civil engineering leaders consider adopting the following guidance for design and construction:

- Steel framed fabric hangars must be designed according to requirements set out in IBC section 3102 and ASCE 55.
- Follow ASCE 55, NFPA 409, and NFPA 701 guidance for Type IIB noncombustible membranes and Type V limited combustibility membranes.
- IBC 3102 permits the use of membranes as long as the roof is at least 20 feet above any floor level.
- The IBC specifies tensile fabric membranes that serve as cladding for a self-supporting frame will not provide lateral restraint for the structural frame members. Therefore, the structural frame members must be designed to be independently stable, should the membrane fail.
- ASCE 55 does not set drift limits on framing that supports fabric structures because membranes are designed to relax throughout their lifespan.
- ASCE 55 stipulates that designers must consider the effects of localized snow loads due to sliding snow on the membrane.
- The designer must account for the nonlinear geometric relationships between applied loads and structural deformation.

- The assumption of superposition of load effects on the structure that is valid for linear elastic behavior of conventional construction is not valid for membrane design.
- When evaluating different load cases, ASCE 55 prescribes different life-cycle factors that account for the deterioration of fabric over time, as well as the unique load case caused by prestressing used in tensile fabric construction.
- During load analysis, ASCE 55 requires that designers evaluate the strength capacity of fabric in both uniaxial directions of warp and weft as well as biaxial strength and tear strength capacity.
- The only serviceability limit imposed is that the structure is detailed such that fabric cladding does not interact with rigid frame members throughout the life of the facility.
- Fabric membrane structures must be designed to avoid disproportionate collapse.
- Fabric membrane must be designed to avoid ponding due to the combination of losses in prestress and concentrated snow or rain loading.
- Adequate prestress of fabric must be designed to avoid slack or zero tension areas throughout the membrane service life.
- The design must include analysis of nonlinear behavior resulting from large deflections of material.
- Fabric hangars must be designed to resist uplift forces with adequate anchoring systems at the foundation.

- Designers must consider shear forces between fabric panels in the design of joint overlaps as well as the horizontal loads implied from the tensioned fabric to its supporting members.
- In order to avoid tears, careful detailing in design is required to avoid stress concentrations in the fabric.
- A structural engineer that specializes in the design of tensile fabric structures is recommended to account for the unique design characteristics of fabric hangars.
- The engineer of record shall deliver drawings that include seaming, anchorage of the fabric, and highlight areas of the membrane that are reinforced against stress concentrations.
- Fabric membrane manufacturers must prove competence in fabric structural analysis software that was used to design the membrane. This ensures no loss of design fidelity between manufacturer and designer.
- Fabric seams will be formed either by high frequency welding, stitching, or taping techniques as directed by material manufacturer specifications.
- Installation crews must pay close attention to the rate of prestressing, which should be gradual and uniform, until the membrane reaches the prescribed design stress.

The above recommendations should be implemented into the current UFCs. Specifically, the recommendations could be input into UFC 4-211-01 in the relevant sections pertaining to the various steps of the hangar design process. A generalized illustration of the design process is outlined in Figure 20.

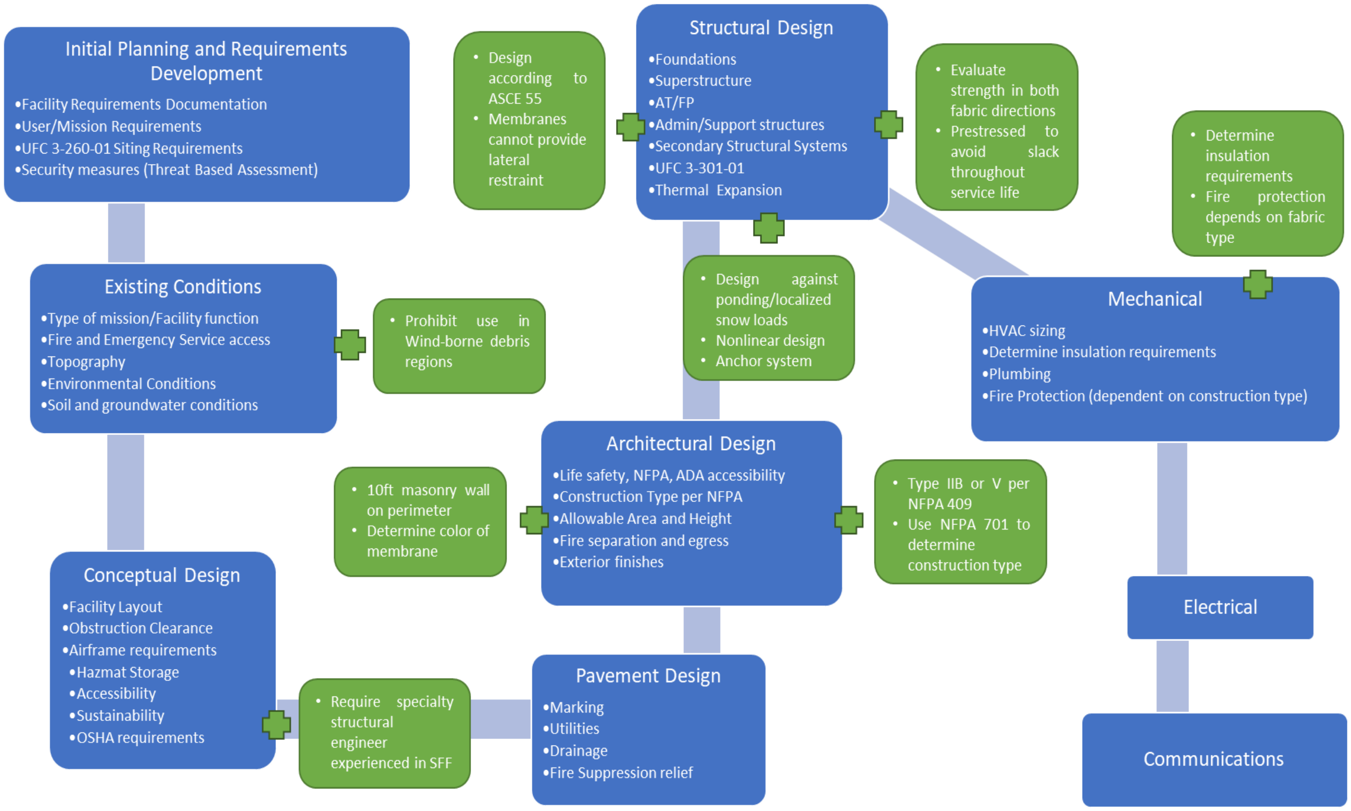


Figure 20. UFC 4-211-01 design process including recommendation for steel framed fabric hangars.

In Figure 20, the existing design process for aircraft maintenance hangars is shown in blue. Additions resulting from the recommendations are summarized in green. Apparent from the diagram, the majority of additions would affect the architectural and structural sections of the UFC.

In order to ensure this information is received by appropriate USAF personnel involved with SFF hangar projects, it is further recommended that training be provided on the topic. This could be in the form of in-residence or distance learning through the use of existing Air Force Institute of Technology (AFIT) Civil Engineer School courses. Alternatively, short computer-based training modules could be developed as a one-time requirement for USAF personnel involved with SFF hangar projects.

Recommendations for Future Research

The structural analysis performed in this research was greatly limited by the capabilities of Abaqus CAE modeling software to analyze large complex structures. There are currently several finite element analysis software that are useful for civil structures such as Strand 7 © that may prove more practical for this type of problem. It is recommended to pursue a complete structural analysis of the entire steel frame fabric hangar. This may expose higher stress areas due to irregular shapes around door frames as well as the performance of a hangar exposed to wind uplift forces that were not captured in this research.

A large part of LCCAs conducted per UFC 1-200-02 include energy performance metrics in the analysis. These was not included in the LCC comparison in this research. A comparison of energy consumption between the types of construction would be useful in light of the DoD's many energy efficiency and conservation initiatives.

This research considered large aircraft hangars meant to support cargo aircraft. Future feasibility research should be conducted for smaller aircraft hangars to determine if construction cost savings is negated due to the reduced facility size.

Lastly, the LCCA performed in this research was conducted on the basis of only the data gathered during case study interviews. Therefore, the power of this research to make general statements about the life-cycle cost effectiveness of fabric hangars is limited. In order to generalize the cost comparison between fabric and conventional hangars, a larger and broader set of cost data inputs is needed for both types of construction.

Appendix A: LCCA Input and Output

Initial Cost	Unit	Quantity	Manufacturer			
			min	max	total min	total max
Steel Frame and exterior fabric	sf	50190	$ 17.00	$ 24.00	$ 853,230.00	$ 1,204,560.00
Insulation and a liner	sf	50190	$ 6.00	$ 10.00	$ 301,140.00	$ 501,900.00
Fabric door	sf	15313.5	$ 80.00	$ 90.00	$ 1,225,080.00	$ 1,378,215.00
Fire Suppression	sf	50190	$ 3.00	$ 3.00	$ 150,570.00	$ 150,570.00
Site Prep and Earthwork	sf	90000				
Standard Foundations	sf	90000				
Slab on Grade	sf	90000				
Structural frame and roofing	sf	90000				
Exterior Walls	sf	90000				
Interior Construction	sf	90000				
Interior finishes	sf	90000				
Plumbing	sf	90000				
Fire Protection		90000				
HVAC		90000				
Electrical		90000				
Insulated Membrane	sf	90000				
subtotal			$ 50.44	$ 64.46	**$ 2,530,020.00**	**$ 3,235,245.00**
Bonding		90000				
Total (Indirect+Direct)						
Maintenance						
Yearly Inspection	ea	1	$ 3,000.00	$ 5,000.00	**$ 3,000.00**	**$ 5,000.00**
Warranty cost	ea	1				
Major Overhauls		20yr+ service life				
Fabric Replacement	sf	50190	$ 4.00	$ 5.00	**$ 200,760.00**	**$ 250,950.00**

Figure 21. Cost data for fabric hangar life cycle cost calculations

Initial Cost	Unit	Quantity	Rockford		Literature		OKC	
				total	min	max		
Steel Frame and exterior fabric	sf	50190			$ 37.16	$ 65.03		
Insulation and a liner	sf	50190			$ 51.34	$ 89.85		
Fabric door	sf	15313.5						
Fire Suppression	sf	50190						
Site Prep and Earthwork	sf	90000	$ 4.91	$ 441,900				
Standard Foundations	sf	90000	$ 4.39	$ 395,100				
Slab on Grade	sf	90000	$ 8.69	$ 782,100				
Structural frame and roofing	sf	90000	$ 1.83	$ 164,700				
Exterior Walls	sf	90000	$ 3.44	$ 309,600				
Interior Construction	sf	90000	$ 6.64	$ 597,600				
Interior finishes	sf	90000	$ 1.92	$ 172,800				
Plumbing	sf	90000	$ 6.28	$ 565,200				
Fire Protection		90000	$ 11.38	$ 1,024,200				
HVAC		90000	$ 6.31	$ 567,900				
Electrical		90000	$ 15.97	$ 1,437,300				
Insulated Membrane	sf	90000	$ 65.00	$ 5,850,000				
subtotal				$ 12,308,400				
Bonding		90000	$ 1.37	$ 123,300				
Total (Indirect+Direct)			$ 138.13	$ 12,431,700.00	$ 23.23	$ 1,165,702.02	$ 199.12	**$ 7,000,000.00**
Maintenance			ACF Adj	**$ 11,104,042.72**	ACF Adj	**$ 1,610,534.56**		
Yearly Inspection	ea	1	$ 123.38		$ 32.09			
Warranty cost	ea	1	**$ 25,000.00**					

Figure 22. Cost data for fabric hangar

Supplemental Information		
Area(sf)	50190	
Door	15313.5	
Rockford Area	90000	
OKC	35154	
square meter to square foot conversion	10.7639	
escalation 04 to 18 from RS Means		1.502
escalation 16 to 18 from UFC 3-701-01		1.040
rockford to OKC		
1.03	0.92	0.893
average unit construction cost (Guard All, Rockford, Lit, OKC)		
$ 87.24		**$ 5,728,051.65**
Min	max	
$ 32.09	$ 123.38	
Average maintenance (warranties and guard-all inspection)	Factor	
11000	1.0814	**$ 11,895.31**
Fabric Overhaul	Factor	
250950	1.0814	**$ 271,375.26**

Figure 23. Cost data for fabric hangar

Initial Cost	Unit	Quantity	UFC Gross Unit Cost	UFC Total	UFC 3-701-01
PRV	sf	50190	$ 292.00	**$ 17,638,502.66**	
Sustainment unit costs (FAC 2111)	sf	50190	$ 0.37	$ 18,595.92	
Keep anything to do with structure and cladding	occurences in desing life	total cost per occurrence	adjusted for area	life cost	
replace aluminum siding 1st floor	1	$ 23,162.64	$ 40,023.86	$ 40,023.86	
"2nd floor	1	$ 28,319.26	$ 48,934.23	$ 48,934.23	
"3rd floor	1	$ 31,439.91	$ 54,326.55	$ 54,326.55	
replace glass 1st floor	40	$ 219.78	$ 219.78	$ 8,791.20	
repair window	2	$ 22,887.53	$ 22,887.53	$ 45,775.06	
repair steel door	2	$ 5,250.28	$ 5,250.28	$ 10,500.56	
refinish steel door	10	$ 287.38	$ 287.38	$ 2,873.80	
replace double roll-up door	1	$ 89,250.13	$ 89,250.13	$ 89,250.13	
minor metal roof finish repairs	8	$ 2,306.87	$ 3,986.15	$ 31,889.23	
metal roof flashing replacement	40	$ 542.84	$ 938.00	$ 37,519.99	
minor panel replacement	2	$ 9,278.34	$ 16,032.50	$ 32,064.99	
total panel replacement	1	$ 265,445.60	$ 458,676.40	$ 458,676.40	
repair med weight vinyl wall covering	40	$ 29.25	$ 50.54	$ 2,021.70	
replace "	2	$ 1,903.19	$ 3,288.61	$ 6,577.23	
UFC assumed area	29046		total sus cost	$ 869,224.92	
study area	50190		per year	**$ 20,102.26**	
area multiplier	1.728		SUC	$ 0.40	

Figure 24. Cost data for conventional hangar life cycle calculations

Supplemental Information	
Hangar Dimensions	
Area(sf)	50190
Door (sf)	15313.5
planning and design factor	1.09
SIOH	1.057
Contingency	1.05
ACF	0.92
Sustainment ACF	0.89
2018 Escalation	1.0394
2016 to 2018 PRV Escalation	1.0404
combined PRV escalation	1.308199
combined SUC escalation	1.081392

Figure 25. Factors used for conventional hangar calculations. Sourced from UFC 3-701-01

NIST BLCC 5.3-17: Summary LCC

Consistent with Federal Life Cycle Cost Methodology in OMB Circular A-94

General Information

File Name:	G:\Thesis\LCC\LCCA.xml
Date of Study:	Mon Jan 15 07:59:47 EST 2018
Analysis Type:	MILCON Analysis, Non-Energy Project
Project Name:	Permanent Large Aircraft Hangar
Project Location:	Oklahoma
Analyst:	Justin Iungerich
Base Date:	April 1, 2018
Beneficial Occupancy Date:	April 1, 2019
Study Period:	40 years 0 months (April 1, 2018 through March 31, 2058)
Discount Rate:	2.8%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are NOMINAL (inclusive of general inflation)

Alternative: Conventional

LCC Summary

	Present Value	Annual Value
Initial Cost Paid By Agency	$17,638,503	$738,637
Energy Consumption Costs	$0	$0
Energy Demand Costs	$0	$0
Energy Utility Rebates	$0	$0
Water Usage Costs	$0	$0
Water Disposal Costs	$0	$0
Routine Annually Recurring OM&R Costs	$681,217	$28,527
Routine Non-Annually Recurring OM&R Costs	$0	$0
Major Repair and Replacement Costs	$0	$0
Less Remaining Value	$0	$0
	------------	------------
Total Life-Cycle Cost	$18,319,719	$767,164

Alternative: Steel Framed Fabric Aircraft Hangar

LCC Summary

	Present Value	Annual Value
Initial Cost Paid By Agency	$5,728,052	$239,870
Energy Consumption Costs	$0	$0
Energy Demand Costs	$0	$0
Energy Utility Rebates	$0	$0
Water Usage Costs	$0	$0
Water Disposal Costs	$0	$0
Routine Annually Recurring OM&R Costs	$403,103	$16,881
Routine Non-Annually Recurring OM&R Costs	$0	$0
Major Repair and Replacement Costs	$235,103	$9,845
Less Remaining Value	$0	$0
	------------	------------
Total Life-Cycle Cost	$6,366,257	$266,596

Figure 25. BLCC 5 Summary LCC Report

NIST BLCC 5.3-17: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology in OMB Circular A-94

Base Case: Conventional

Alternative: Steel Framed Fabric Aircraft Hangar

General Information

File Name:	G:\Thesis\LCC\LCCA.xml
Date of Study:	Mon Jan 15 07:58:22 EST 2018
Project Name:	Permanent Large Aircraft Hangar
Project Location:	Oklahoma
Analysis Type:	MILCON Analysis, Non-Energy Project
Analyst:	Justin Iungerich
Base Date:	April 1, 2018
Beneficial Occupancy Date:	April 1, 2019
Study Period:	40 years 0 months (April 1, 2018 through March 31, 2058)
Discount Rate:	2.8%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$17,638,503	$5,728,052	$11,910,451
Future Costs:			
Energy Consumption Costs	$0	$0	$0
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Routine Recurring and Non-Recurring OM&R Costs	$681,217	$403,103	$278,114
Major Repair and Replacements	$0	$235,103	-$235,103
Residual Value at End of Study Period	$0	$0	$0
	------------	------------	------------
Subtotal (for Future Cost Items)	$681,217	$638,206	$43,011
	------------	------------	------------
Total PV Life-Cycle Cost	$18,319,719	$6,366,257	$11,953,462

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$278,114
- Increased Total Investment	-$11,675,348

Figure 26. BLCC 5 Comparative Analysis Report

Appendix B: Design Load Calculations

Wind Loads		Chapter 30				
Directional Method						
exposure cat C, risk category II						
fundamental frequency, n1	0.662	beta	0.2	Kd	0.85	
h	75.28	Rn	0.067	Kzt	1	
Vz	178.9319	R	0.142057093	z-bar	48.45	
L	200	Gust Factor, Gf	0.860518173	GCPi	0.55	
B	244	Iz	0.140700169	Kh	1.191	
etah	1.281173	Q	0.827102905	Kz	1.23	
etaB	4.152579	z	85.44	qz	35.39645	
etaL	11.39518	Lz	539.9157203	qh	34.27412	
Rh	0.499411	V	115	qh(15)	24.46096	h/L = 0.38
Rb	0.211826			qh(45)	30.79203	
RL	0.083906			qh(60)	32.51869	

Figure 27 Factors used in wind load calculations

qz	35.39645		roof angle, rad	0.083776						
qh	**34.27412**									
									qz	**qh**
Walls									-0.55	**0.55**
Component	Zone	height	V pressure, q	length	width	Effective A	GCp	(-)GCp	(+)Pres	(-)Pres
<20sf (W)	4	75.3	34.3			20	0.9	-0.9	**50.33805**	
50sf (W)	4	75.3	34.3			50	0.81	-0.81	47.25105	
200sf (W)	4	75.3	34.3			200	0.69	-0.79	43.13505	
>500sf (W)	4	75.3	34.3			500	0.6	-0.7	40.04805	
<20sf (L/S)	4	75.3	34.3			20	0.9	-0.9		**-49.7208**
50 sf(L/S)	4	75.3	34.3			50	0.81	-0.81		-46.6338
200sf (L/S)	4	75.3	34.3			200	0.69	-0.79		-45.9478
>500sf (L/S)	4	75.3	34.3			500	0.6	-0.7		-42.8608
<20sf (W)	5	75.3	34.3			20	0.9	-1.8	50.33805	
50sf (W)	5	75.3	34.3			50	0.81	-1.56	47.25105	
200sf (W)	5	75.3	34.3			200	0.69	-1.21	43.13505	
>500sf (W)	5	75.3	34.3			500	0.6	-1	40.04805	
<20sf (W)	5	14	24.46096			20	0.9	-1.8	41.48291	
50sf (W)	5	14	24.46096			50	0.81	-1.56	39.28142	
200sf (W)	5	14	24.46096			200	0.69	-1.21	36.34611	
>500sf (W)	5	14	24.46096			500	0.6	-1	34.14462	

Figure 28. Cladding and Components wind load calculations

									qz	**qh**
Roof				tributary area measurements					0.55	**-0.55**
Component	Zone	height	V pressure, q	length	width	Effective A	GCp	(-)GCp	(+)Pres	(-)Pres
<10sf	1	75.3	34.3			10	0	-1.4		**-66.8708**
50sf	1	75.3	34.3			50	0	-1.2		-60.0108
200sf	1	75.3	34.3			200	0	-1		-53.1508
>500sf	1	75.3	34.3			500	0	-0.9		-49.7208
<10sf	2	75.3	34.3			10	0	-2.3		-97.7408
50 sf	2	75.3	34.3			50	0	-2		-87.4508
200sf	2	75.3	34.3			200	0	-1.79		-80.2478
>500sf	2	75.3	34.3			500	0	-1.6		-73.7308
<20sf	3	75.3	34.3			10	0	-3.2		**-128.611**
50sf	3	75.3	34.3			50	0	-2.81		-115.234
200sf	3	75.3	34.3			200	0	-2.53		-105.63
>500sf	3	75.3	34.3			500	0	-2.33		-98.7698
RJ5	1	75.3	34.3	33	14	462	0	-0.91		-50.0638
RJ5	2	75.3	34.3	33	14	462	0	-1.62		-74.4168
RJ5	3	75.3	34.3	33	14	462	0	-2.35		-99.4558
RJ6	1	75.3	34.3	38	14	532	0	-0.9		-49.7208
RJ6	2	75.3	34.3	38	14	532	0	-1.6		-73.7308
RJ6	3	75.3	34.3	38	14	532	0	-2.3		-97.7408
				(-)	(+)			min positiv	16	
		roof	Max deck load, psf	-54.0165	6.72					
			Conventional design uses 20 Ga, PLN3 Roof Decl							

Figure 29. Wind load calculations

Dead Load			Cladding	Truss	Lateral	Effective Area	
Weight of Fabric	45.5	oz/SY	0.316	0.316	0.316	12436.45	
Standing Seam Metal Roof			1.5	1.5	1.5		
Metal Deck			2.5	2.5	2.5		
3" Rigid Insulation			4.5	4.5	4.5		
MEP			0	1.5	1.5		
slope adjustment (1:12)			0.03	0.04	0.04		
Misc			0.4	1.9	1.9	Point Load	
Conv. Total Roof DL			8.93	11.94	11.94	148491.213	
Fab Total Roof DL			5.246	8.256	8.256	102675.3312	
Wall Dead Load							
CMU + Metal Panel		Back Area	Sides	total Area			
CMU	0	15158.23	10075	25233.23			
Gypsum Board	2.8						
Metal Panel	3			Pt Load			
	5.8			73176.35			
Fabric Wall							
Fabric	0.316						
Gypsum	2.8			pt Load		Fab Weight	Conv Weight
	3.116			39313.36		141988.6958	221667.5655

Figure 30. Dead load calculations

Risk Cat	II		
Importance Factor	1		
PGA	16		
Ss	0.27		
S1	0.08		
Ss,5/50	0.016		
S1,5/50	0.05		
Ss, 10/50	0.09		
S1, 10/50	0.03		
Ss, 20/50	0.04		
S1, 20/50	0.02		
Site Class C			
Structure type: all other structures			
Fv	1.7		
Fa	1.2		
Sms	0.324		
Sm1	0.136		
Sds	0.216		
Sd1	0.090667		
Design Cat	B		
Structural Height	87.5		
R	3.25		
Overstrength	2		
Def Amp Factor, Cd	4		
No vertical or horizontal irregularities			
Equivalent lateral force procedure section 12.8			
Seismic Response Coefficient, Cs	0.066462		
Ct	0.02		
x	0.75		
Ta=T	0.572184		
Upper Limit Cs	**0.048756**		
Tl	12		
Lower Limit Cs	0.009504		Fabric
Effective Weight, W	221.6676	kip	141.9887
Seismic Base Shear, V	**10.80763**	kip	**6.922804**

Figure 31. Seismic load calculations

Live Loads			
LR1	Trib Area	Concentrated Load	Factored
20	330.525	6610.5	**4957.875**
LR2	Trib Area	Concentrated Load	
20	661.05	13221	**9915.75**
LR3	Trib Area		
20	660.8875	13217.75	**9913.3125**
LR4	area	Concentrated Load	
20	1321.775	26435.5	**19826.625**
LR5	area	Concentrated Load	
20	558.025	11160.5	**8370.375**
LR6	area	concentrated load	
20	1116.05	22321	**16740.75**

Figure 26. Reducing roof live load to point load for input into Abaqus

Roof Dead Loads		
Load	12	
DR1	Trib Area	Concentrated Load
12	330.525	3966.3
DR2	Trib Area	Concentrated Load
12	661.05	7932.6
DR3	Trib Area	
12	660.8875	7930.65
DR4	area	Concentrated Load
12	1321.775	15861.3
DR5	area	Concentrated Load
12	558.025	6696.3
DR6	area	concentrated load
12	1116.05	13392.6

Figure 27. Reducing dead load to point loads

Walls (Front/Back)												
Load	5.8											
Node	DW1	DW2	DW3	DW4	DW5	DW6	DW7	DW8	DW9	DW10	DW11	DW12
Trib Area	104.7033	278.664	277.704	306.15	612	522	469.43	938.4	800.4	484.7375	969	826.5
Concentrated Load	**607.3**	**1616.3**	**1610.7**	**1775.7**	**3549.6**	**3027.6**	**2722.7**	**5442.7**	**4642.3**	**2811.5**	**5620.2**	**4793.7**
Walls (sides)												
Node	DWs1	DWs2	DWs3	DWs4	DWs5	DWs6	DWs7	DWs8				
Trib Area	65	130	243.75	487.5	373.75	747.5	385.9375	771.875				
Concentrated Load	**377.0**	**754.0**	**1413.8**	**2827.5**	**2167.8**	**4335.5**	**2238.4**	**4476.9**				
	Zone 1	Zone 2	Zone 3									
Wind (Roof)	-66.9	-97.74	-128.6									
Node	WR1	WR2	WR3	WR4	WR5	WR6						
Zone 1 area	92.69	449.8	396.5325	1321.775	334.815	1116.05						
Zone 2 area	68.835	211.25	264.355	0	223.21	0						
Zone 3 area	169	0	0	0	0	0						
Concentrated Load	-34662.2939	-50739.195	-52366.08195	-88426.748	-44215.669	-74663.745						
0.75*0.6*	-15598.03226	-22832.63775	-23564.73688	-39792.036	-19897.051	-33598.685						
0.6*	-20797.37634	-30443.517	-31419.64917	-53056.049	-26529.401	-44798.247						
0.42*	**-14558.16344**	**-21310.4619**	**-21993.75442**	**-37139.234**	**-18570.581**	**-31358.773**						

Figure 28. Dead and wind loads on walls reduced to point loads

Wind (Walls X) windward								
Node	WWx1	WWx2	WWx3	WWx4	WWx5	WWx6	WWx7	WWx8
Zone 4 area	39	130	146.25	487.5	224.25	747.5	231.5625	771.875
Zone 5 area	26	0	97.5	0	149.5	0	154.375	0
concentrated load	3272.1	6544.2	12270.375	24540.75	18814.575	37629.15	19428.09375	38856.188
0.75*0.6*	1472.445	2944.89	5521.66875	11043.338	8466.5588	16933.118	8742.642188	17485.284
0.6*	**1963.26**	**3926.52**	**7362.225**	**14724.45**	**11288.745**	**22577.49**	**11656.85625**	**23313.713**
Wind (Walls X) leeward	WWxl1	WWxl2	WWxl3	WWxl4	WWxl5	WWxl6	WWxl7	WWxl8
area	65	130	243.75	487.5	373.75	747.5	385.9375	771.875
concentrated load	-3231.8	-6463.6	-12119.25	-24238.5	-18582.85	-37165.7	-19188.8125	-38377.625
0.75*0.6*	-1454.31	-2908.62	-5453.6625	-10907.325	-8362.2825	-16724.565	-8634.965625	-17269.931
0.6*	**-1939.08**	**-3878.16**	**-7271.55**	**-14543.1**	**-11149.71**	**-22299.42**	**-11513.2875**	**-23026.575**

Figure 29. Wind loads reduced to point loads

Wind (Walls Z) windward								
Node	WWz1	WWz2	WWz3	WWz4	WWz5	WWz6	WWz7	WWz8
Zone 4 area	104.7033	278.664	277.704	306.15	612	522	469.43	938.4
Zone 5 area	0	0	0	0	0	0	0	0
concentrated load	5270.764122	14027.94576	13979.61936	15411.591	30808.08	26277.48	23631.1062	47239.056
0.75*0.6*	2371.843855	6312.575592	6290.828712	6935.216	13863.636	11824.866	10633.99779	21257.575
0.6*	3162.458473	8416.767456	8387.771616	9246.9546	18484.848	15766.488	14178.66372	28343.434
0.42*	**2213.720931**	**5891.737219**	**5871.440131**	**6472.8682**	**12939.394**	**11036.542**	**9925.064604**	**19840.404**
Wind (Walls Z) leeward	WWzl1	WWzl2	WWzl3	WWzl4	WWzl5	WWzl6	WWzl7	WWzl8
area	104.7033	278.664	277.704	306.15	612	522	469.43	938.4
concentrated load	-5205.848076	-13855.17408	-13807.44288	-15221.778	-30428.64	-25953.84	-23340.0596	-46657.248
0.75*0.6*	-2342.631634	-6234.828336	-6213.349296	-6849.8001	-13692.888	-11679.228	-10503.02682	-20995.762
0.6*	-3123.508846	-8313.104448	-8284.465728	-9133.0668	-18257.184	-15572.304	-14004.03576	-27994.349
0.42*	**-2186.456192**	**-5819.173114**	**-5799.12601**	**-6393.1468**	**-12780.029**	**-10900.613**	**-9802.825032**	**-19596.044**

Figure 30. Wind loads reduced to point loads

Pressures		
Roof		
Membrane Part	TM1	
Dead	5.25	
Factored Live Load	15	
Factored Wind (0.75)(0.6)	30.105	
Factored Wind (0.6)	40.14	
WallsWindward		WallsLeeward
0.75*0.6	22.653	-22.374
0.6*	30.204	-29.832

Figure 31. Factored distributed loads for use in fabric model

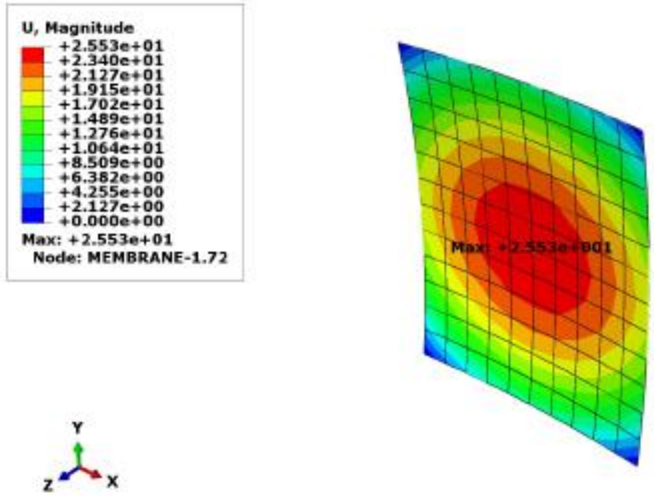


Figure 32. Output of example used for convergence tests with 120 elements

M3D4R Elements						
5psi load (much higher than necessary, just useful for visuals)						
Element Count	Umax (in)	S(mises) max (psi)	increments	increment min		
500	24.05	3.80E+04	500	1.00E-16		
2000	23.44	3.60E+04	500	1.00E-16		
1200	24.62	3.98E+04	500	1.00E-16	stopped early	
1200	24.79	4.04E+04	500	1.00E-36	stopped early	
2000	24.75	4.02E+04	500	1.00E-36	too many attempts	
120	**25.53**	**4.26E+04**	**500**	**1.00E-36**		
6	13.308	8.18E+03	500	1.00E-36		
average	22.926857	3.50E+04				
standard dev	4.2911812	12009.17045				
confidence level						
Mesh density needed (elements/sf)	**0.0904733**	120 elements				
example area	1326.3575					

			U	S	
Conf Level	Z-value	Confidence Interval (CI) max	Min	CI Max	CI Min
90%	1.645	25.59	20.26	42471.72	27538.28
80%	1.285	25.01	20.84	40837.67	29172.33
70%	1.035	24.61	21.25	39702.91	30307.09
95%	1.96	**26.11**	**19.75**	**43901.52**	**26108.48**

Figure 33. Summary of convergence study to select mesh density for M3D4R elements

To estimate the increase in tension in the membrane surface due to an applied wind pressure:

1) Identify cross section with the least curvature concave to the load.

2) Approximate the curvature with a circular arc. This may be done directly or calculated from chord length and sag. (Figure 5-12)

$$R = (C^2 + 4S^2)/8S \quad (5.4\text{-}1)$$

R = Radius
C = Chord length
S = Sag

3) Calculate the tensile force necessary to resist a uniform pressure on the estimated circular arc.

$$T = P*R \quad (5.4\text{-}2)$$

T = Tension
P = Pressure
R = Radius

Figure 34. Excerpt from Tensile Fabric Structures by the TC on TFS. Shows process used to estimate tensile force in the membrane. Chord Length was taken to be 40.81ft, Sag was 1.413ft as determined from Abaqus as the max deflection, and the prestress of 411.12 lb. /ft. was added to equation 5.4-2 to determine the tensile force. To calculate the stress, the tensile force was divided by 0.003ft, the manufacturer provided membrane thickness.

Appendix C: Fabric Membrane Specifications

SHEERFILL® I Architectural Membrane

Tensile Modulus – Poisson's Ratio

Technical Bulletin

MSAJ/M-U2-1995

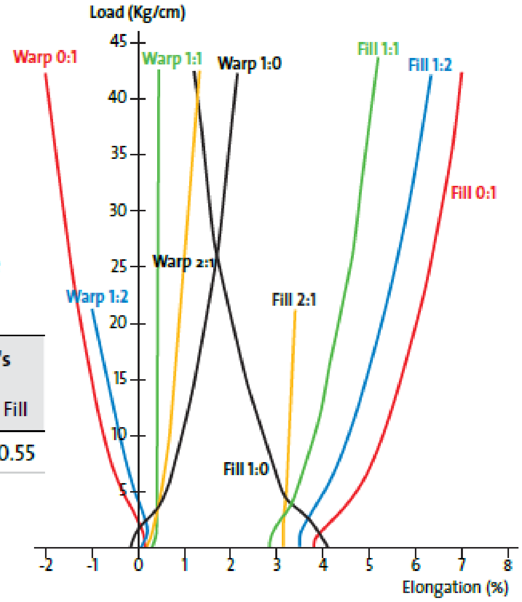
Rev A | November 2013

Two of the most important pieces of information needed in designing a tensile structure are the Tensile Modulus and Poisson's Ratio of the membrane material. There are various methods used to calculate these values. One of the most accepted was developed by the Membrane Structures Association of Japan (MSAJ). The membrane is subjected to biaxial stress at different loadings ratios (warp to fill). Results are then used to calculate the two values. In this bulletin, we have graphic information on the results of the biaxial tests and values for Tensile Modulus and Poisson's Ratio.

SHEERFILL® I Architectural Membrane

Actual Value For Material Constants

Fabric	Tensile Modulus (kgf/m)		Poisson's Ratio	
	Warp	Fill	Warp	Fill
SHEERFILL I	186,600	127,900	0.81	0.55



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SAINT-GOBAIN

Figure 35. Saint-Gobain © provided specifications for Sheerfill I ® membrane

SHEERFILL® I

SHEERFILL®

SHEERFILL® I

SHEERFILL Architectural Membrane is the original permanent tensioned membrane. SHEERFILL I was the first developed and remains the product of choice for applications where a very high strength to weight ratio is required to meet the demands of long spands, and high winds or snow loads.

All SHEERFILL membranes conform to rigid fire and building codes for permanent structures.

Typical Properties

Property	Value	Test Method
Coated Fabric Weight (oz/yd^2)	45.5 nominal	ASTM D4851-88
Thickness (in)	0.036 nominal	ASTM D4851-88
Breaking Strength (lb/in) **Strain Rate: 2 in/min** Warp Fill	1025 min. avg. 950 min. avg	ASTM D4851-88
Breaking Strength (lb/in) **After Crease Fold** Warp Fill	800 min. avg. 755 min. avg	ASTM D4851-88
Trapezoidal Tear (lb) Warp Fill	100 min. avg. 130 min. avg.	ASTM D4851-88
Solar Transmission (%)	10 nominal	ASTM E424
Solar Reflectance (%)	73 nominal	ASTM E424
Burning Characteristics Flame Spread Smoke Generation	5 max 5 max	ASTM E84 Tunnel Test
Incombustibility of Substrates	Pass	ASTM E136
Fire Resistance of Roof Coverings Spread of Flame & Intermittent Flame	Class A	ASTM E108
Flame Resistance	Pass	NFPA 701, Small Scale
Color	White (after exposure to sunlight)	-
Reinforcement Construction	Warp B150 4/3 Fill B150 4/3	Count W18 x F19

Values listed are for virgin roll goods only. Appropriate industry safety factors need to be used to account for the in-service effects of handling, weathering, etc.

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Limited Warranty: For a period of 6 months from the date of first sale, Saint-Gobain Performance Plastics Corporation warrants this product(s) to be free from defects in manufacturing. Our only obligation will be to provide replacement product for any portion proving defective, or at our option, to refund the purchase price thereof. User assumes all other risks, if any, including the risk of injury, loss or damage, whether direct or consequential, arising out of the use, misuse, or inability to use this product(s). SAINT-GOBAIN PERFORMANCE PLASTICS DISCLAIMS ANY AND ALL OTHER WARRANTIES, EXPRESSED OR IMPLIED, INCLUDING THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE.

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SAINT-GOBAIN

Figure 36. Sheerfill I ® material specifications

Appendix D: Case Study Interview Responses

General Questions

The first group of questions that follow are general questions that were given to most participants, independent of category.

Question 1: What do you like about the structure?

Facility Managers/Owners:

All three participants from this category were asked Question 1. This category of participants liked the transparency of fabric membrane hangars, the aesthetics or appearance of the structure, and faster construction when compared to conventional construction. Participant A mentioned that "the hangar can only maintain a 20 degree [Fahrenheit] temperature difference from outside temperatures," which requires workers to wear cold-weather clothing during the cold seasons of Oklahoma.

Contractor/Manufacturer:

Participant E liked the speed of construction, claiming that, "when compared to a metal building, it [fabric clad building] usually goes up at least twice as fast."

Participant F commented on the adaptability of fabric construction and the ability customize an order to customer needs. Similar to the facility managers, Participant F liked the translucency of fabric structures. Participant F also liked the light weight, clear spans, and ease of maintenance. Participant F also stated that fabric membranes "…last longer. The fabric membrane we use lasts longer than a typical steel sheeting. Our own factory is clad with the membrane we manufacture, and the factory membrane is 35 years old."

Participant G answered Question 1 from the perspective of conventional construction. Participant G stated that when working with the DoD, it is easier to design with steel due to requirements set out in the UFC. Participant G had experienced fabric construction with projects that involved vertical lift fabric doors (VLFDs). It was noted that VLFD structural design is challenging and Participant G assumed that adding fabric to the rest of the structure could pose a similar challenge for design.

USAF PM/AFCEC Staff:

Participant K liked the quickness of construction typically seen with temporary fabric structures used by the USAF. It was also noted that fabric structures are easy to modify if utilities need relocating. Participant K had experienced a project where several permanent aircraft hangars were constructed with fabric membranes. According to Participant K, these facilities had a great maintenance and repair demand due to poor construction of the steel structural frame.

Question 2: If you had a chance to do the project again would you use the same method of construction?

Facility Managers/Owners:

Participant A claimed that given the circumstances during project planning, they would have chosen fabric construction again. Participant A's response was based on a shorter construction period and considerably lower cost.

Participant B, however, was more nuanced and answered that the decision depends on the climate. Participant B's climate favored the choice of fabric construction, but they claimed that in a colder climate it may make more sense to use conventional construction methods.

Participant C answered that they probably would build with fabric construction again given their circumstances.

USAF PM/AFCEC Staff:

Participant H was hesitant to recommend using fabric construction again in reference to the Oklahoma City hangar. They were concerned with the perceived fragility of fabric aircraft hangars and the lack of information related to that type of construction.

Participant K, said that they would not recommend fabric construction for permanent hangars in overseas locations, since the contractors had proven unreliable in this type of construction.

Question 3: What would you change if you could?

Facility Managers/Owners:

Participant A would add insulation to their structure.

Contractor/Manufacturer:

In general, Participant F would like to make the fabric structures manufactured by their company more visually appealing.

Participant E would like to make general product improvements to remain efficient and competitive as a company.

Question 4: Why was this type of construction chosen?

Facility Managers/Owners:

Participant C stated that fabric construction was chosen initially for budget limitations of the owner and that the airport favored the low impact to radio frequency (RF) signals that was shown in fabric membrane hangars.

Participant A chose fabric construction due to a short construction timeline and the ability to meet USAF mission bed-down timeline.

Contractor/Manufacturer:

Participant G stated that their company has consistently chosen conventional construction methods because it has a long history of success. They were also concerned with the ability to insulate a tensile fabric clad hangar.

USAF PM/AFCEC Staff:

This category has chosen conventional construction in the past due to low life-cycle costs of steel clad hangars.

Question 5: Why is the USAF interested in these types of structures?

Questions 5 through 8 were only given to Participant I who was initially assigned the task of investigating the practicality of using tensile fabric on aircraft hangars. Participant I stated that, the USAF was interested in an assessment of pros and cons of fabric steel hangars. They were also interested in a comparison of life-cycle costs, compatibility with UFC requirements, and the maintainability of the hangars. The participant stated that one of the drivers of this research was the bed-down of new missions and the need to do this in a timely and life-cycle cost effective manner.

Question 6: Why would the USAF try to find alternatives to conventional construction?

The participant stated that the relative large cost to the USAF budget of hangar construction drives interest from leadership. The participant also stated that, these projects require large amounts of material to cover large spans and therefore, research into material alternatives has the potential to save significant amounts in construction costs.

Question 7: Is the USAF hesitant about using fabric construction? And if so, why?

The participant stated that the USAF is hesitant, and that the major concerns with fabric construction are: limitations imposed by the environment of certain AFBs, the lack of information about projects using fabric construction, and uncertainty about the amount of personnel and labor hours required to maintain these type of hangars.

Question 8: What are some advantages/disadvantages of the structures?

The participant stated that from their review of manufacturer published information, fabric hangars were significantly lighter weight structures than conventional. The participant noted that daylighting typical of fabric membranes would help the USAF with sustainability efforts. The participant predicted disadvantages such as higher operation and maintenance costs of the facility lifecycle and membrane vulnerability to puncture from projectiles.

Design Questions

Questions 9 through 14 focus on the design of fabric and conventional hangars. These questions were directed at the Contractor/Manufacturer category with overlap on some questions with other categories.

Question 9: Are there limitations due to the environment?

Facility Managers/Owners:

Participant A was able to answer this question since they were involved with the project development from design to present day operation. They mentioned that cold climates were a concern. They provided an anecdote of how the steel clad hangars that Participant A operated were damaged in wind storms and needed repairs when the fabric clad hangar only needed repairs due to debris impact from the adjacent steel hangar. Participant A was concerned that it may be difficult to attach insulation to their existing hangar.

Contractor/Manufacturer:

Participant F stated that the structures that their company designs and constructs are not limited by the climate. They have been able to construct facilities on the coast of Japan with design wind speeds of 240mph. Their PVC/PES membranes have been used successfully on facilities in hot climates such as Yuma, AZ, and cold climates such as the Arctic Circle. The participant pointed out that they are currently designing a membrane coating to protect against 200deg F internal facility temperatures. Their company provides insulation options (with R-values of up to R-35) that do not cause condensation issues. However, the participant mentioned this does significantly raise the facility cost.

Question 10: What experience did the firm have with this type of design?

Participant F's company started in 1967, and has been operating in the U.S since 1983.

Question 11: How was the contractor selected, and were there many options?

Facility Managers/Owners:

Participant A stated that there were limited options for contractors that specialized in tensile fabric construction in 2006. The contractors were selected by a team that represented the many users of the MROTC site outside of Tinker AFB.

Contractor/Manufacturer:

Participant F stated that their company is typically hired by a general contractor (GC) as a subcontractor. The participant mentioned that there is currently a lot of direct competition for the service and product they provide.

Question 12: What are some common mistakes in design?

Contractor/Manufacturer:

Participant F stated that in their experience working with U.S. government (USG) customers, some of the common mistakes in design include: uneducated bid review teams, reviewers being fooled by faulty information supplied by contractors, wrong codes cited in the design of the fabric hangar, fake calculations, and designs that are not stamped by a professional engineer (PE). Participant F also stated that a significant fraction of their business comes from renovation of poorly designed facilities, owned by the USG. The root of these mistakes, as Participant F claims, is that US military personnel reviewing designs do not understand the technical requirements of tensile fabric hangars.

USAF PM/AFCEC Staff:

Participant K experienced a fabric hangar construction project where several hangars had been poorly constructed and the owner was stuck with a warranty agreement that placed a heavy burden on the installation's maintenance personnel. Participant K had several recommendations for avoiding these issues in the future. They recommended that project manager pay close attention to installation, especially where the membrane has to make tight turns around the structural frame. In maintenance, Participant K stressed that owners catch tears in the fabric early to avoid large repairs to the membrane. The participant also stressed the importance of a detailed warranty and that project managers should note the DoD typically inspects aircraft hangars every five years with only an annual roof inspection.

Question 13: If fabric was used, what type was chosen and why?

Facility Managers/Owners:

Participant A and B used PVC/PES due to low cost.

Contractor/Manufacturer:

Participant F's company uses a 28oz PVC/PES and offers 20-yr warranty on the fabric. The participant stated that the membrane has 400-500lb/in tensile strength. They do not use PTFE/Glass because it is too expensive for the incremental increase in lifespan. They state that PVC/PES is easier to install, and is more appropriate for flat panels typical of the structures they build.

Question 14: What design changes, if any, were required due to AF/DoD specific requirements?

Contractor/Manufacturer:

Participant G stated that with conventional hangars that use VLFDs, the hangar is typically classified as low occupancy for anti-terrorism/force protection (AT/FP) design requirements. Participant G also stated that the USAF requires fall protection systems to be designed such that they are not inconvenient to use.

Participant D stated that they design above and beyond the requirements of the IBC, ASCE 7, American Institute of Steel Construction (AISC), and Unified Facility

Guide Specifications (UFGS) that are required by the USAF and DoD. Specifically the participant's company uses higher safety factors in their design than is required. Participant D echoed Participant G, by saying that hangar bays are typically classified as low occupancy when VLFDs are used.

Construction Questions

Questions 15 through 21 were again directed at the Contractor/Manufacturer category with overlapping input from the other categories.

USAF PM/AFCEC Staff:

Participant J remarked that the USAF has had difficulty with steel framed fabric contractors not providing the required design calculations.

Question 15: Did difficulties arise during construction? If yes, what?

Facility Managers/Owners:

Participant A said the only difficulties during construction were due to cold weather delaying the placement of foundation concrete.

Contractor/Manufacturer:

Participant G stated that they commonly have a problem with low bidding contractors and subcontractors during construction. They mentioned that the Federal Aviation Administration (FAA) construction waiver process can sometimes cause construction timeline delays. Participant G stated that in general working on an AFB raises the cost of construction. In Participant G's experience with VLFDs, the required heavier support structures imply larger construction equipment.

Participant F stated that typically when constructing fabric hangars, wind is the only cause for delay because the membrane has to be installed at low winds.

Participant E stated that fabric construction has difficulties common to all projects such as site restrictions.

Question 16: How does fabric construction differ, if at all, from conventional construction in execution?

Facility Managers/Owners:

Participant A stated during the project to build the three-hangar MROTC site, the fabric clad hangar was built in six months and the two conventional steel hangars were constructed in 18 months. However, it's worth noting that the steel hangars were approximately two and a half times the size of the fabric hangar.

Participant C's two 300ft by 300ft hangars were constructed in 12 months in a project that included demolition of existing hangars, storm water utility renovation, and replacement of a concrete parking apron.

Both Participant A and C described the process of membrane installation. According to the participants, the steel frame of the hangar is erected first, then iron workers install the membrane on the frame in sections, incrementally securing fabric panels and tensioning them to the frame. Participant C stated that the joints between fabric panels were HF-welded together. Participant C also noted that the project was in design throughout the construction process.

Contractor/Manufacturer:

Participants F and E described a similar construction process to that of the Facility Managers.

Participant E stated that their company is able to install the membrane without the need of workers on the roof. This participant echoed the concern of high winds during membrane installation, and that this can be mitigated by working at the night. Participant E stressed the importance of seam layout to avoid water ponding on the membrane. Additionally this participant stated that fabric panels are manufactured to match the width of the steel frame bays which simplifies installation to the frame.

USAF PM/AFCEC Staff:

Participant J remarked that fabric construction seems to have the potential for shorter construction timelines than conventional construction.

Question 17: What are common sources for delay?

Participant C stated that the subcontractor selected for their hangar project had never done a project of this size as of 2016 when the Rockford hangars were built. The participant stated that the subcontractor had difficulty with HF welds on the membrane and that after completion there were leak issues with the membrane caused by the welds that took the contractor eight months to correct. This eight month period was concurrent with the 12 month project schedule according to Participant C.

Question 18: Does weather affect fabric hangar construction differently than conventional construction methods/projects? If so, how?

Facility Managers/Owners:

Participant C stated that the only weather issue was the limitation of installing the fabric membrane in low winds.

Contractor/Manufacturer:

Participant D stated that their product is not limited by weather because at the point of VLFD installation, the rest of the built structure can shelter the VLFD from wind.

Participant E echoed the limitations imposed by the wind. They also stated that extreme cold temperatures (-30 to -40 degrees F) cause minor contractions of their fabric membranes and therefore more care must be taken during the tensioning process in these conditions.

Question 19: Does QA/QC differ when constructing fabric hangars vs conventional construction methods/projects? If so, how?

Facility Managers/Owners:

Participant A stated there was no major difference in quality assurance/quality control (QA/QC) during the fabric hangar's construction. Participant A did reference the Engineering Technical Letter (ETL) 2-15 when writing the design specifications, but that ETL is no longer used and has been superseded by UFC 4-211-01.

Contractor/Manufacturer:

Both Participants D and F stated that fabric is subject to different material testing procedures per NFPA 701. Participant D stated that these tests typically span a few weeks.

Participant E specified that there is a separate QC process for the steel components of the structure to that of the fabric membrane. This participant stated that inspectors are trained to look for cold welds in fabric membrane joints, which is a common issue when installing membranes.

USAF PM/AFCEC Staff:

Participant J has had difficulty obtaining material properties from fabric manufacturers on past projects. This participant has also experienced contractors that make incorrect assumptions in design calculations. This includes an example of foundation anchors designed for soil anchoring instead of permanent foundation requirements.

Question 20: How many companies were available to construct facility in solicitation process?

Contractor/Manufacturer:

Participant G stated that, regardless of location, conventional hangar construction does not have issues obtaining competitive bids. This participant also noted that the scale of hangar projects and associated costs attract contractors from a relatively wide range of locations. Participant G stated that there is an exception for remote areas that have been known to pose problems in attracting subcontractors.

Participants D and E stated that they typically see between six and ten close competitors on projects.

USAF PM/AFCEC Staff:

Participant I stated that there seems to be a relatively smaller pool of contractors in fabric construction compared to the practically unlimited pool for conventional hangars. However, Participant I did not think that the amount of contractors was so low to require sole source selection on projects.

Question 21: With differing standards (government and industry) for fabric hangars, what method/s were used to hold the contractor accountable (i.e. contract clauses, documents, etc.)?

Participant D stated that the development of a VLFD UFGS has helped. They stated that prior to the UFGS, every manufacturer had their own specifications.

Maintenance Questions

Questions 22 through 27 were directed at the Facility Manager/Owner category with overlap from other categories where relevant.

Question 22: Who is in charge of maintenance?

Facility Managers/Owners:

All of the participants in this category had contracted with the fabric membrane manufacturer for maintenance of the membrane.

Contractor/Manufacturer:

Participant F said that their company is comfortable with either letting the customer perform their own maintenance or setting up a service contract to maintain the user’s facility. This participant stated that the 20-year warranty includes required inspections. Also if the customer contracts out the installation, Participant F’s company will perform the initial inspection after construction.

Participant G has typically experienced the installation/user taking on the responsibility of maintenance for conventional hangars.

Participant D stated that their company has in-house capabilities to provide maintenance contracts on their VLFDs.

USAF PM/AFCEC Staff:

In Participant K’s experience with the overseas fabric hangars, the U.S. Army had assigned civilian maintenance personnel for the facilities. This proved problematic due to the limited manning at the location and high man-hour requirements imposed by the warranty. Participant K stated that the installation was searching for contractor solution to provide maintenance.

Participant J stated that maintenance for aircraft hangars is typically provided by the base. This participant also noted that per AFI 21-136, a maintenance plan is required for USAF-owned sun shade structures (Department of Defense).

Question 23: Are there any typical warranty calls?

Facility Managers/Owners:

Participant A indicated that the only time the installer was called out, was the instance of metal debris from the adjacent hangar penetrating the fabric hangar's membrane.

Contractor/Manufacturer:

Participant G stated that in conventional hangars, leaks in the cladding are a common problem that the customer will have to call on the warranty for.

Participant D stated that their company will typically be called out to make initial adjustments to the membrane tension rods after installation once the membrane has acclimated to the environment.

USAF PM/AFCEC Staff:

Participant K stated that structural failures due to faulty construction were under warranty as claimed by USG.

Question 24: What type of warranty comes with the facility?

Facility Managers/Owners:

Participant B stated that their initial warranty had already expired, but is now under a maintenance service contract.

Contractor/Manufacturer:

Participant F stated that their company offers a 20-year warranty that requires a maintenance contract with the company to include annual inspections.

Question 25: How does the maintenance of this facility differ, if at all, from a conventional hangar?

Facility Managers/Owners:

Participant C stated that the membrane manufacturer provided patch kits and that a local contractor provides personnel for maintenance.

Contractor/Manufacturer:

The common response from all participants was that maintenance for fabric hangars is patching tears and leaks, re-tensioning the fabric and cables, and cleaning the fabric if desired by the owner. Participants stated that approved patch kits are provided by the installer for repairs.

Participant D mentioned that their company recommends a six-month walk around of the VLFD and an annual fabric wear inspection.

USAF PM/AFCEC Staff:

Participant K stated that the installation maintenance crew had performed patch repairs on the hangars.

Both participants I and J thought that maintenance on fabric hangars would be technically less difficult, but they were hesitant in regards to the longevity of the fabric.

Question 26: Are there different maintenance concerns for the fabric hangar than what is typical of a conventional hangar? If so, what?

Facility Managers/Owners:

Participant B stated that small patch repairs were performed by the installing contractor. They also stated that they had a unique problem of birds being attracted to the structure due to the natural lighting. Participant B was able to solve this problem by adding netting below the roof structural members.

Participant A stated that the tensioning rods are accessible and regularly maintained on annual maintenance calls. This participant stated that overall the fabric hangar is low maintenance and that practically no maintenance has been performed on the fabric membrane over its 11 years of operation.

Contractor/Manufacturer:

Participant D compared fabric to conventional hangar maintenance by saying that replacing the fabric membrane is equivalent to repainting a conventional hangar.

Question 27: How much downtime has maintenance caused?

Facility Managers/Owners:

Participant B was given an estimate of 30 days to replace the membrane due to the unique shape of the hangar’s horizontal sliding door.

Contractor/Manufacturer:

The participants in this category stated that for fabric construction, maintenance and repair of the membrane causes minimal downtime. The common response was that user would only be effected if the repair was to an entire fabric panel, or if the entire membrane was being replaced.

USAF PM/AFCEC Staff:

Participant K indicated that patch repairs did not cause mission downtime.

Facility Operation Questions

Questions 28 through 30 were directed at the Facility Manager/Owner category with overlap from the other categories where relevant.

Question 28: What level of training is required to adequately manage the facility?

Facility Managers/Owners:

Participant C stated that the local fire department had never dealt with a fabric hangar outside of the military and had to adopt new procedures to reflect new NFPA requirements corresponding to the new type of construction.

Contractor/Manufacturer:

Participant F stated their facilities require practically zero maintenance. The participant stated that the owner should easily be able to operate the door system. Participant F noted that owners need to identify tears in the fabric and inspect the facility for areas that need re-tensioning after an extreme weather event. This participant also noted that they had constructed a building in Newfoundland that constantly experiences 50mph wind gusts. The membrane on this facility requires re-tensioning annually.

Participant G echoed the statement that hangar door systems do not require much training. This participant noted that the user should be familiar with bridge crane operation procedures and OSHA requirements for inspection if that is part of the facility. Participant G emphasized that biggest concern for facility managers is correct operation and maintenance of fire suppression system to avoid costly accidental discharges.

USAF PM/AFCEC Staff:

Participant I stated that high winds limit operations of door systems and the facility manager should be familiar with those limitations to avoid damage to the structure.

Question 29: Are there changes that have to be made to the way users operate within the hangar compared to a conventional hangar? If so, what?

Facility Managers/Owners:

Participant B stated that the daylighting has increased the productivity and morale of workers in their hangar.

Participants A and B stated that they are limited on the type of aircraft that can be used within the facility by the size of the hangar. Both participants stated that this should be caught in the design process to accommodate anticipated size of aircraft used in the facility.

Contractor/Manufacturer:

Participant D noted that door operation is limited at high winds. This participant stated that horizontal sliding doors are limited at wind speeds greater than 35 mph and VLFDs are restricted at speeds greater than 60 mph.

USAF PM/AFCEC Staff:

Participant K, said that operations were impacted because missions had to be relocated out of the failed fabric hangars.

Question 30: Are there limitations to operations in the fabric structure vs conventional? If so, what?

Contractor/Manufacturer:

Participant G stated that height of a conventional hangar is limited due to imaginary surface restrictions when the facility is built near the flight line.

Participant D stated that VLFDs are vulnerable to puncture by users impacting the fabric with equipment. Therefore, the participant recommends the users maintain awareness of this vulnerability when operating near the VLFDs.

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14. ABSTRACT
Through the life of the United States Air Force (USAF), the accepted method for constructing permanent aircraft hangars is the use of materials such as steel and concrete. However, the emerging type of construction known as steel framed fabric (SFF) construction shows potential to meet the requirements of the USAF at a lower life-cycle cost and with faster construction delivery. A comprehensive comparison to conventional hangars is conducted through the means of an extensive literature review, case study analysis, structural analysis with the use of finite element analysis (FEA) software, and a life-cycle cost comparison. Through examination of Department of Defense (DoD) Unified Facility Criteria, industry building codes and best practices, there are no significant barriers keeping the USAF/DoD from constructing SFF hangars. The FEA of a simplified SFF model reinforced that fabric membranes can provide equal, if not more, structural safety in comparison to conventional hangar claddings. This research recommends the USAF implement SFF hangars as an alternative to conventional construction for new aircraft hangar projects. By investing in SFF, the USAF will save considerable costs to the US taxpayer. Shorter construction delivery times will allow commanders more flexibility in mission bed-down. Lastly, reduced maintenance concerns typical of SFF hangars will lessen the burden on facility maintenance personnel.

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