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Licenciado em Ciências de Engenharia Mecânica

Electro-Optical/Infrared sensor turret integration on an aircraft - structural impact on LOCKHEED MARTIN C-130H and design methodology

Dissertação para obtenção do Grau de Mestre em Engenharia Mecânica

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Dissertação apresentada à Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa para a obtenção do grau de Mestre em Engenharia Mecânica

Setembro 2015

Aos que sacrificaram quase tudo para me dar tudo, aos meus pais.

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To my friends for all the comprehension and support.

And most importantly to my family, to whom I owe everything.

"*Треба нахилиться, щоб з криниці води напиться*"

Abstract

The growing need to patrol and survey large maritime and terrestrial areas increased the need to integrate external sensors on aircraft in order to accomplish those patrols at increasingly higher altitudes, longer range and not depending upon vehicle type.

The main focus of this work is to elaborate a practical, simple, effective and efficient methodology for the aircraft modification procedure resulting from the integration of an Electro-Optical/Infra-Red (EO/IR) turret through a support structure. The importance of the development of a good methodology relies on the correct management of project variables as time, available resources and project complexity. The key is to deliver a proper tool for a project design team that will be used to create a solution that fulfils all technical, non-technical and certification requirements present in this field of transportation. The created methodology is independent of two main inputs: sensor model and aircraft model definition, and therefore it is intended to deliver the results for different projects besides the one that was presented in this work as a case study. This particular case study presents the development of a structure support for FLIR STAR SAPHIRE III turret integration on the front lower fuselage bulkhead (radome) of the LOCKHEED MARTIN C-130 H. Development of the case study focuses on the study of local structural analysis through the use of Finite Element Method (FEM).

Development of this Dissertation resulted in a cooperation between Faculty of Science and Technology - Universidade Nova de Lisboa and the company OGMA - Indústria Aeronáutica de Portugal

Keywords: EO/IR Sensor; Aeronautics; Structural Analysis; European Aviation Safety Agency; Finite Element Analysis; LOCKHEED MARTIN C-130 H; FLIR STAR SAPHIRE III

Resumo

A crescente necessidade de reconhecimento e vigilância de grandes áreas terrestres e marítimas implicou o desenvolvimento da integração de sensores EO/IR exteriores em aeronaves de forma a efetuar o patrulhamento a altitudes cada vez mais altas, de maior alcance e através de vários tipos de veículos.

O grande foco deste trabalho passa pela elaboração de uma metodologia de um projeto de modificações de uma aeronave prática, simples, clara, eficiente e eficaz resultante do estudo da integração de uma torreta de um sensor Electro-Ótico/Infravermelho. A correta definição de uma metodologia é de grande importância de forma a obter uma correta gestão das variáveis de projeto como o tempo, alocação de recursos e a complexidade do projeto. O objetivo centra-se em desenvolver uma ferramenta útil para uma equipa de projeto de forma a obter uma solução final que cumpre requisitos técnicos, não técnicos e requisitos de certificação, presente neste tipo de indústria. A metodologia desenvolvida é independente tanto do modelo do sensor a instalar como a aeronave a ser modificada, de forma a poder ser empregue em projetos diferentes do caso presente neste trabalho. O caso de estudo apresenta (através do uso da metodologia) o desenvolvimento de uma estrutura de suporte para a torreta do sensor FLIR STAR SAPHIRE III. Esta estrutura é especificamente desenvolvida para a aeronave LOCKHEED MARTIN C-130 H. O desenvolvimento do caso de estudo é focado na análise estrutural através da análise de elementos finitos.

O desenvolvimento desta Dissertação resulta da cooperação entre a Faculdade de Ciências e Tecnologia - Universidade Nova de Lisboa e a empresa OGMA - Indústria Aeronáutica de Portugal, S.A

Palavras-Chave: Sensor EO/IR; Aeronáutica; Análise Estrutural; EASA; Análise de Elementos Finitos; LOCKHEED MARTIN C-130 H; FLIR STAR SAPHIRE III

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Acronims and nomeclature

AC - Air Conditioning

APF - Aerodynamic Pressure Force

APU - Auxiliar Power Unit

b/t = ratio between width (b) and thickness (t) of a C-channel section.

BEW - Basic Empty Weight

BEM - Basic Empty Moment

c = End fixity coefficient

CCM - Certification Compliance Matrix

CG - Center of Gravity

$CG_{\%MAC}$= CG position with respect to MAC length

CS - Certification Specification

CVE - Compliance Verification Engineer.

DAF - Dynamic Amplification Factor

DOA - Design Organization Approval.

DOF - Degree of Freedom

DSM - Design Structural Matrix

E = Modulus of Elasticity

EASA - European Aviation Safety Agency

EMC - Electromagnetic compatibility

EMA - Experimental Modal Analysis

EO - Electro-optical

Fcc - Critical crippling Stress

FEA - Finite Element Analysis

FEM - Finite Element Method

G - Universal gravitational constant

I - Moment of Inertia

IR - Infrared

IPB - Internal Parts Breakdown

k = Number of stress evels considered in the analysis

L = Effective length

LEMAC - Leading Edge of Mean Aerodynamic Chord arm

MAC - Mean Aerodynamic Chord

MLW - Maximum Landing Weight

MTOW - Maximum Take-off Weight.

MOC - Mean Of Compliance

MS - Margin of Safety

MZFW - Maximum Zero Fuel Weight

NA - Neutral Axis

NHAA - Negative high angle of attack

n_i= Number of loading cycles at i^{th} stress level

N_i= Number of loading cycles at i^{th} stress level

NLAA - Negative low a [1]ngle of attack

OEW - Operating Empty Weight

P_{cr} = Critical Buckling Load

PHAA - Positive high angle of attack

PLAA - Positive low angle of attack

Q_x = First moment of inertia along x

σ_{VMES} = VMES equivalent stress

σ_{11} = Normal stress in plane 1 and in direction 1

σ_{11} = Shear stress in plane 2 and direction 3

t = thickness

$V_y = Shear\ force\ along\ y$

TC - Type Certificate

STC - Supplemental Type Certificate

VMES - Von Mises Equivalent Stress

τ = Shear Stress

δ_s = Shearing deformation

ω_n = Natural Frequency

ω_f = Forced Frequency

1 Introduction

1.1 Objectives and structure

In the following development of this Master Thesis, the underlying purpose is to develop a methodology for the integration of a Electro-Optical (EO) and Infrared (IR) sensor turret in a military type aircraft. This project is related to the branch of aeronautics and its elaboration results from a cooperation between the Faculty of Science and Technology - Universidade Nova de Lisboa and OGMA - Indústria Aeronáutica de Portugal, S.A.

Integration of EO/IR sensor turret on an aircraft presents three major areas of study: structural impact, aerodynamic impact and system integration impact. This project is focused on the structural impact of sensor turret integration. Following a brief analysis of what is an EO/IR sensor, a complete methodology is developed in order to elaborate a Preliminary Design of a structural solution for integration of sensors of this nature on an aircraft. Nerveless, this work is conducted simultaneously with aerodynamic impact study by Costa [1], whose results will be considered further in this work.

Developing a methodology for a project design is often related to the perfect balance between cost, deadline and scope of work. The calibration and establishment of each aspect directly influences the two major factors that will define a project, expected quality result and the resources available with the time and cost invested in this project. Thus, usually a project design team must define the expected result, trying to achieve it with all of the relative factors.

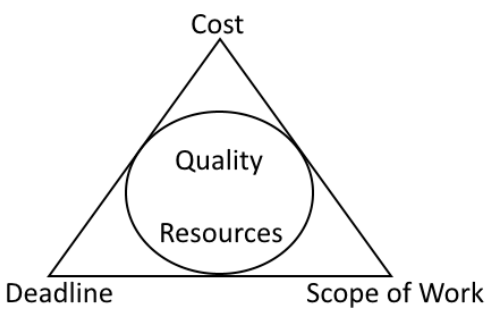


Fig. 1-1 Iron triangle adaptation[2].

Carrying out this work, this thesis is divided in several sequential milestones distributed along 8 chapters:

- EO/IR sensors breakdown (Chapter 2)
- Modification design overview (Chapter 3)
- Feasibility analysis of turret installation on a military aircraft (Chapter 4)
- State of the art of theoretic assumptions during the modification project analysis (Chapter 5)
- Modification requirements settlement for the project - case study (Chapter 6)
- Project design process - case study (Chapter 6)
- Structure analysis of the final solution -case study (Chapter 6)
- Turret integration methodology definition (Chapter 7)
- Final remarks and conclusions about the future work to be done (Chapter 8)

Among the presented sensors in Chapter 2 that resulted from a market study survey, the sensor to be studied and that is considered in this project is the one that is most common among the installations in these type of aircraft model. The vehicle type to be studied is airborne, thus, the aircraft model to be considered is *LOCKHEED MARTIN C-130 H* (general characteristics on Fig. 1-2). C-130 is itself a compound of numerous variants. The "H" variant was chosen for this subject due to its popularity and its great abundance in this market. Due to the fact that Portuguese Air Force has 3 C-130H and 3 C130H-30 [3] (extended modification of "H" variant nicknamed as Super-Hercules) in its fleet 3, is probably also one of decisive factors to engage the "H" variant.

The structure of an airborne vehicle is complex and so a preliminary analysis of the most suitable location for the turret integration is needed. The development of chapters as Chapter 4 "Feasibility analysis of turret integration on different aircraft locations" will consist on an analysis of the considered aircraft model, however the developed methodology is valid in any airborne vehicle. After the selection process of the optimum location for the turret integration, a more detailed analysis of the local structure is required, which is conducted during the Chapter 6, Case Study.

Weights and loads	Value
Operating Empty Weight (OEW)	75 562 lbs | 34 274 kg
Max. Fuel Weight	45 900 lbs | 20 819 kg
Max. Payload (2,5 G conditions)	41 790 lbs | 18 955 kg
Max. Normal T-O Weight	155 000 lbs | 70 305 kg
Max. Overload T-O Weight (MTOW)	175 000 lbs | 79 380 kg
Max. Normal Landing Weight	130 000 lbs | 58 965 kg
Max. Overload Landing Weight (MLW)	155 000 lbs | 70 305 kg
Max. Zero Fuel Weight (2,5 G conditions)	117 350 lbs | 53 230 kg
Max.Wing Loading	88.83 lb/sq ft | 433.7 kg/m^2
Max. Power Loading	8.44 lbs/shp | 5.14 kg/kW
External Dimensions	**Value**
Wing Span (A)	132.6 ft | 40.41 m
Length overwall (B)	97.75 ft | 29.79 m
Height overall (C)	38.8 ft | 11.84 m
Tailplane span (D)	52.7 ft | 16.05 m
Wheel track	14.25 ft | 4.34 m
Propeller diameter	13.5 ft | 4.11 m
Wing area (gross)	1745 sq. Ft | 162,12 m^2
Performance (at MTOW)	**Value**
Max. Operating Speed (above 15 000 ft)	270 KIAS | 140 m/s
Max. Diving Speed (above 15 000 ft)	320 KIAS | 16 m/s
Ceiling	33 000 feet | 10 000 m

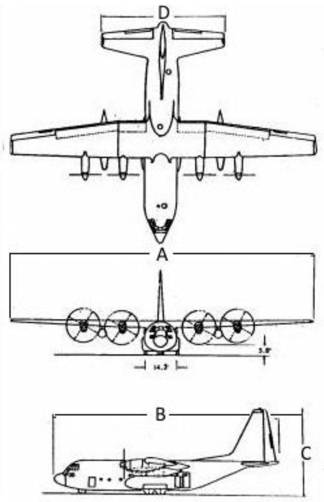


Fig. 1-2 LOCKHEED MARTIN C-130 main characteristics[4]

This chapter will focus only on the preliminary design of *FLIR STAR SAPHIRE III* support structure in the front bulkhead of the considered aircraft model. Concluding the chapter, the consideration of the EO/IR sensor model can be varied but the technical specification of the aircraft model makes it somehow difficult to adapt to other vehicle of the same nature. However, the methodology that is developed is to be adapted and considered for similar aircraft models. During the project design process, it is intended to create a support structure that connects the aircraft and the EO/IR sensor turret support plate, as defined in Fig. 1-3

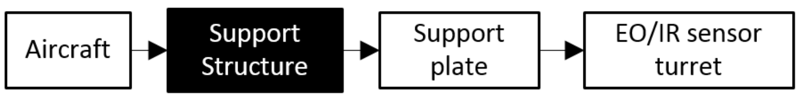


Fig. 1-3 Framework of the project development focus

Being concluded the Case Study, comes the time to define the output of this project in Chapter 7, Methodology definition. The focus of this methodology is gathered in detailing the Preliminary design of the project, and defining the needed procedure at each step. Finally, Chapter 8 will held the main project conclusions and suggestions for further work. Concluding, the final objectives of this project are:

- To develop an universal feasibility analysis of EO/IR sensor turret installation location for any aircraft model;
- To develop a support structure for integration of *FLIR STAR SAPHIRE III* on *LOCKHEED MARTIN C-130 H;*

- To develop a practical, simple and effective methodology that can deliver a preview of the structural impact analysis and the development of a support structure for the EO/IR turret in an aircraft.

1.2 Motivation

During the last three decades, the rising demand to fulfil some of the needs of civil and military entities led to the growing and development of the external sensor technology. Nowadays, this external sensor market is wide enough to offer the right solution in accordance with the mission purpose and the vehicle type (land, airborne or maritime) in which these sensors are mounted. The process of integrating one of these sensors on an airborne vehicle is a joint venture between technical certification and design project.

Certification reveals to be a fundamental milestone in airborne transportation in order to guarantee the compliance of numerous safety and environmental requirements worldwide. In aviation, safety depends greatly on 3 factors [5]: men (pilots, maintenance mechanics, air traffic controllers and other personnel that is involved in this industry), the environment (external factors that can, or cannot, influence the flight conditions), and the machine (understood as the aircraft in which the flight is performed, its operational status and airworthiness). Operational status of an aircraft is understood as the quality of its operational behaviour, as airworthiness is possession of the necessary requirements for flying in safe conditions, within allowable limits (clear definition found in Italian RAI-ENAC Technical Regulations).

Aircraft operability and airworthiness certification is currently managed by numerous national and international entities. In Portugal, the agency responsible for aircraft certification is INAC (Instituto Nacional de Aviação Civíl). There is also an European entity which, with cooperation of national entities, controls the certification procedures. Called EASA (European Aviation Safety Agency) currently defines the certification procedures and requirements about all of the airborne transportation in European airspace. The worldwide entity which manages and ensures the growth of international civil aviation is ICAO (International Civil Aviation Organization). In Europe, airworthiness and operability regulation can be summarized by Fig. 1-4.

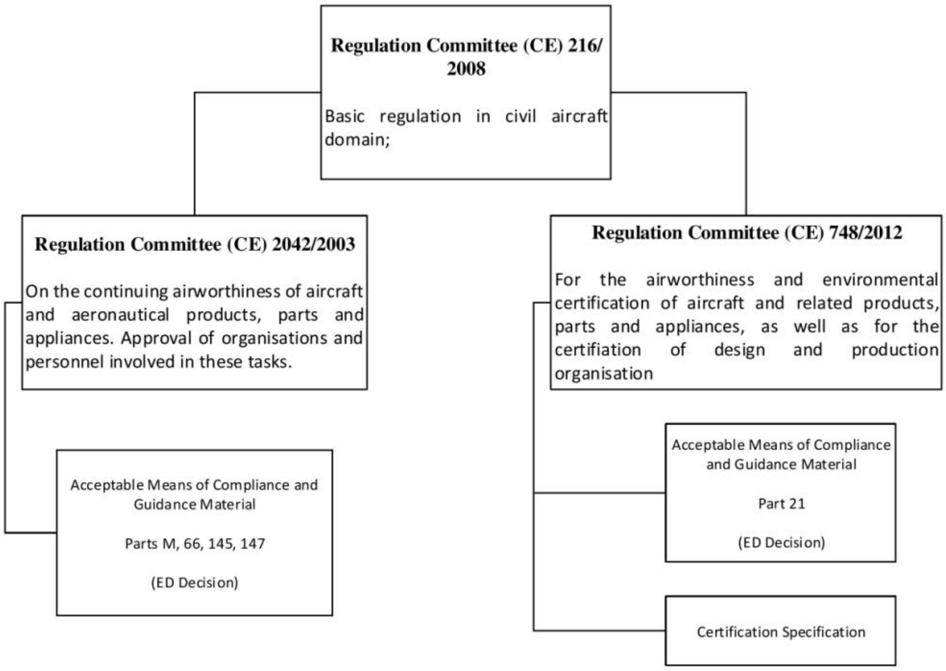


Fig. 1-4 EASA - Regulation

In accordance with Regulation Committee (CE) 748/2012, OGMA is a Design Organization Approval (DOA) entity. A DOA entity is authorized to perform maintenance and modification in Large Aircrafts (Certification Specification 25) and Light Aircrafts (Certification Specification 23). These maintenance and modification are authorized in avionic installations; electrical systems, structures and interiors, among others.

Acceptable Means of Compliance and Guidance Material - Part 21 is relative to airworthiness, in which occurs the certification of all design and maintenance projects. Part 21 is the branch of certification which is the focus of this study, more specifically sub part B,D,E and M (Type Certification; Changes; Repairs).

The procedure of an aircraft modification approval depends largely from its modification type: Minor or Major. It is considered that a modification is Minor if: it has a negligible effect on aircrafts mass or its Centre of Gravity (CG); no modification to the original airframe is required (not considering possible local reinforcements). Otherwise, the modification is rated as Major. A DOA entity is normally authorized to design and approve a Minor modification to be made. In case of a Major modification, however, a DOA entity is required to apply for a Supplemental Type Certificate (STC). In order to understand the nature of an STC document, one must first understand the meaning of a Type Certificate (TC):

- TC - Issued by the regulator (EASA). An aircraft model which is allowed in European airspace has a document which states that the aircraft was manufactured according to a design which complies with airworthiness requirements. This document contains information about the aircraft performance category, maximum weight limits, engine models, minimum crew, requirements of the Certification State; maximum passengers and other operating limitations.
- STC - Issued by the regulator (EASA). Document which states the approval of a Major modification in compliance with airworthiness and what are the changes to the operating limitations present in the original TC document of an aircraft model. TC also holds any new certification requirements to be met or reviewed after this modification.

From a preliminary analysis to other similar or not aircraft modification projects, it is suggested that the modification is rated Major. It is important to highlight the word "suggestion" once the definition of the modification type can only be done by an experienced member of the Design Team.

This work embraces a modification of an aircraft with Maximum Take Off Weight (MTOW) of about 79 380 kg. Thus, this project will be referred to the certification of Large Aircrafts (CS-25) which is related to any aircraft which MTOW > 5670 kg. Certification of an aircraft in this field requires the accomplishment of numerous Certification Requirements (CS) through study of various static (strength and structural stress) and dynamic (fatigue and damage tolerance) analysis. In the planning of an aircraft modification design project, one must follow a structure of well defined procedures adopted by an DOA entity.

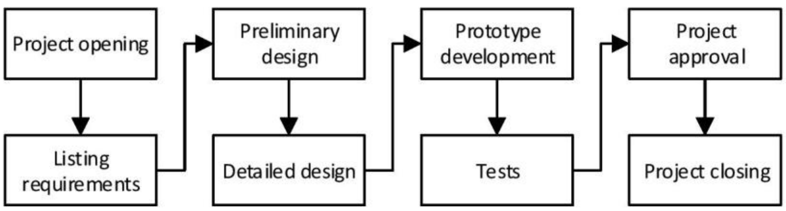


Fig. 1-5 Main milestones during the development of a modification design

Preliminary design, which is the core focus of this project, relies in creating a solution for the turret support structure, its analysis and justification of several CS and non-CS requirements defined for the modification. This work relies in justification of these requirements by static analysis, more specifically material yield phenomena, buckling and crippling.

The study of all the described phenomena will be done recurring to an Finite Element Analysis (FEA) software. FEA is an analysis method approximation to a complex problem, with a complex geometric domain by dividing this domain into finite number of simpler sub domains, called finite elements. Further, the analysis of each element and their respective interrelation is understood based on theoretic assumptions and governing equations depending on the type of analysis and on FEA software in use. FEA reveals to be suited for far more complex problems then analytic approximation and not as costly as experimental analysis. In accordance with the necessary project design procedures of the support structure, all justification and calculation is approached from a conservative way, in order to guarantee a satisfactory safety factor.

The project design and the characterization of beam section for each support structure element is done by engineering judgement and engineering background research. Phenomena as shear stress distribution over a transverse section, eccentric loading, consideration of neutral loading axis and estimation of geometric properties as moment of inertia considerations are implicit over this thesis and their theoretic explanation is not present.

2 Insight of EO/IR sensors

In this chapter, a robust approach is proposed on electro-optical (EO) and infrared sensors (IR), their fundamentals and their respective market use. A sensor is defined as an object that detects signals and information of the surrounding environment. The EO and IR capabilities of a sensor settle the spectral band, namely the interval of different types of information which the sensor receives. For the purpose of this particular study, these sensors are part of airborne observation systems. Depending on the application, several sensor types can be integrated in a turret that is fixed to the aircraft, which is the case. Target phenomenology often dominates the choice of spectral band of use by the sensor, but not entirely. The band choice is also influenced by vagaries of atmospheric transmission and scattering [6].

EO/IR systems are greatly dependent on either target reflection by outer radiation (solar, moonlight or artificial) or the radiation of the target itself. Namely, a majority of EO/IR systems do not apply radiation directly at a target (using a standard video-camera with an integrated flashlight in dark environment can be taken as an example). Therefore, these systems are called passive [6].

Speaking of EO and IR, one must first understand the basics of each technology. What mainly distinguishes EO sensors from IR sensors are the different waveband, or spectrum, in which each one of these receives the information. EO sensors typically receive information in the 0.4-3.0 μm waveband. This interval contains the visible spectrum to our eyes (0.38-0.75 μm). That is why, the operation of these sensors may, in some way, be related to the way our eyes work (which can also be understood as a type of sensors). Like human eyes, EO sensors track the radiation that is reflected from a target due to outer radiation. On the Fig. 2-1 is shown an example of the information received by a EO system. The targets (three men) are visible only due to their reflection of the radiation emitted by the vehicle headlight.

Fig. 2-1 - Image captured by EO sensor of the L-3 WESCAM MX-15HDI [7]

On the contrary, IR sensors group is defined by equipments which capture the radiation that is emitted by a certain target. These sensors generally operate on a waveband between 0.7-14 μm. This is understood as a wide interval in which there is a number of different sub-classes of IR sensors [1]. Fig. 2-12 is an example of an image captured by an IR sensor. The image was captured by an U.S. Navy Lockheed P-3 Orion during search and rescue mission of an Egyptian ferry *Al Salam Baccaccio* in 1998. At the rear of the ferry, the visible white dots are the crew and passengers to be rescued.[8]

Table 2-1Types of IR sensors

IR sensor class	Operation Waveband [μm]
Near-Infrared (NIR)	0.7-1.1
Shortwave-Infrared (SWIR)	1.1-3
Midwave-Infrared (MWIR)	3-5
Longwave-Infrared	8-14

Nowadays, most of EO/IR sensors on the market are fit do adapt to either ground, maritime or airborne vehicles. Particularizing the case, once integrated on an aircraft these sensors can provide a wide range of applications. Intelligence, Surveillance and Reconnaissance (ISR); border-coastal patrol; and ground force protection are the most common missions of these systems in military purpose activities. A EO/IR sensor is divided into different subparts like Operator Console and Turret, this last one particularly important for the purpose of this study. The turret is the external part of the sensor, namely, the part that is located outside the airplane and which integration on the aircraft is the output expected in this dissertation. An example of a EO/IR turret is shown on Fig. 2-3.

Fig. 2-2 Image captured by U.S. Navy LOCKHEED MARTIN P-3 Orion during search & rescue mission

Fig. 2-3 - Example of an EO/IR sensor turret [9]

Currently, the market supply of EO/IR turret is surprisingly wide with more than 15 manufacturers found, including *LOCKHEED MARTIN*, *L-3 WESCAM*, *FLIR*, and others. From the research on the available products in the category of EO/IR turrets, a comparison is made between the models and their main characteristics. At this point, urges the issue of defining what are truly important characteristics of a EO/IR sensor turret for the purpose of this study.

Consulting various available turret data-sheets on the market, specifications like sensor capability, resolution and zoom ratio were outward to the importance of this project. Thus, the important characteristics to be taken into consideration are general dimensions, geometry and weight of each turret model. Table 2-2 presents the main considered models, their relevant characteristics and a brief comparison. Verifying the already existing EO/IR sensor integrations for this aircraft model, one specific model came up as the most utilized, *FLIR STAR SAPHIRE III*.

Table 2-2 Comparion table of different EO/IR models highlighting the chosen for this project.

Manufacturer	Model	Turret weight (kg)	Diameter (m)	Height (m)	Fixed Wing	Area (m^2)
AIRBUS Defence & Space[10]	Arghos II	≈ 43	0,45	0,50	undefined	0,70
AIRBUS Defence & Space [10]	Goshawk II	≈ 30	0,45	0,35	undefined	0,49
Israel Aerospace Industries[11]	MOSP 3000	≈ 32	0,50	0,38	yes	0,60
Raytheon[12]	NA/ AAS- 52	≈ 60	0,46	0,19	yes	0,28
FLIR[13]	Star Saphire III	≈ 44	0,38	0,45	yes	0,54
General Dynamics[14]	V-14	≈70 (system weight)	0,45	0,50	yes	0,71
Northrop Grum-man[15]	NA/AAQ-28(V)	≈ 210	0,41	*-	yes	-
Lockheed Martin[16]	INFIRNO	≈ 58,5	0,40	0,54	yes	0,68
L3 WESCAM[17]	MX 15	≈ 45	0,39	0,48	yes	0,60
L3 WESCAM [18]	MX 20	≈ 90	0,53	0,67	yes	1,12
L3 WESCAM[19]	MX 25	≈ 100	0,65	0,78	yes	1,57
RAFAEL[20]	Toplite EOS	≈ 65	0,59	0,66	yes	1,23

In all of the presented information about *FLIR STAR SAPHIRE III*[13], it is important to highlight that the equipment is qualified for MIL-STD-810 and MIL-STD-461. MIL is a United States Military Standard for equipment certification. Further contractual, design and qualification procedure should be in compliance with certifications presented above.

- MIL-STD-810 - equipment verified to be able to sustain the limit conditions which it will experience during service life (environmental stress, possible equipment defects, among others);
- MIL-STD-461 - electromagnetic compatibility (EMC) in either energy reception or propagation. EMC settles the possibility of various equipments within a small perimeter whose functionality can occur in parallel without unwanted effects.

3 Modification Design Procedure

Normally, a DOA entity has a developed Modification Design plan which it follows in case of a modification project for a civilian aircraft. A Modification Design plan document is usually a flowchart or a compound of flowcharts with well established guidelines in accordance with the regulator procedures. The modification project in this particular study is not of a civilian type, but military. In cases of a military type modification, there are no defined procedures with a regulator to be followed. Normally, a DOA entity has the regulator privileges to proceed in its will in this type of modification. Taking as an example, in a military and state aircraft modification project, change approval and change modification can be done entirely by a DOA entity. It is up to the client to accept or to not accept the modification procedures to be made. However, a military type modification can be conducted in accordance with a civilian type procedure which is commonly accepted by a given client. Thus, the DOA entity Modification Design plan based on civilian type modification is particularized for this project. During this chapter, this particularization is explained in three tiers of detail, which can be observed in Fig. 3-1, where this tiers are divided in columns. The focus of this study will set on Preliminary Design and its development, but before exploring it, an understanding of the whole process is needed.

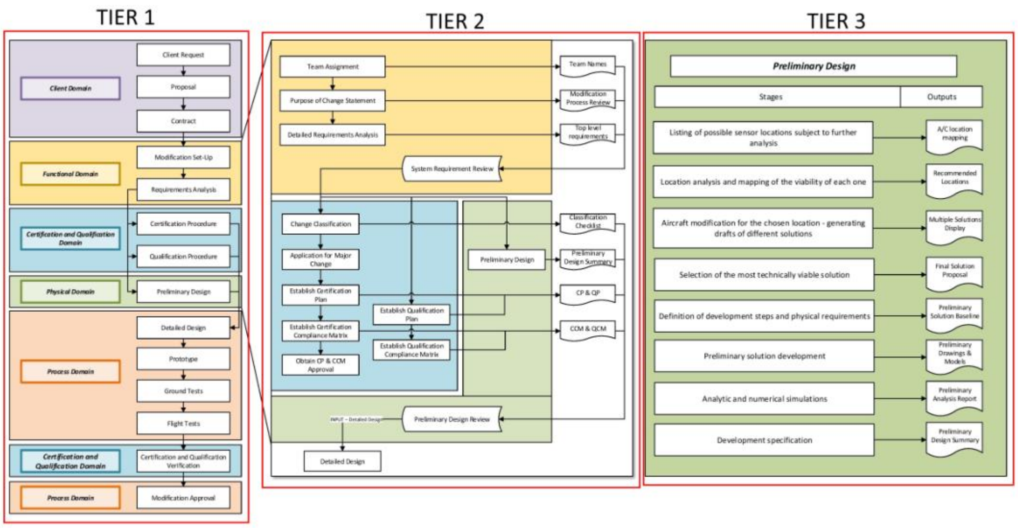


Fig. 3-1 - Modification Design Overview of the turret modification project.

Beginning with the top level tier of detail, usually a modification project is divided into several steps of procedure which are often sequential, as shown on Fig. 3-2. These steps are referred as domains, each one of them being characteristics of certain type of procedure. The act of evoking the "domain" characterization is intended to recall the Axiomatic Design theory for a better understanding and segregation of the Modification Design plan. Axiomatic Design is a systems design methodology that uses matrix methods to systematically analyse the transformation of customer needs in functional requirements, design parameters, and process variables[21]. Axiomatic Design is particularly useful for this type of projects because it allows to define simply what is needed (Costumer Domain), what it needs to do (Functional Domain), how it is suppose to look (Physical Domain) and how to create it (Process Domain). The left side of Fig. 3-2 shows an example of interaction between different domains in common Axiomatic Design project. After a brief observation it is clear that the normal process follows a sequential order. However, the same is not applied on this particular project, as can be observed on the right side of the same Fig. 3-3. During the Preliminary Design phase, there is a number of decisions to be made during the process elaboration that recur to the Functional Domain. Thus, during the Preliminary Design is witnessed a constant interaction between these two domains, Functional and Physical.

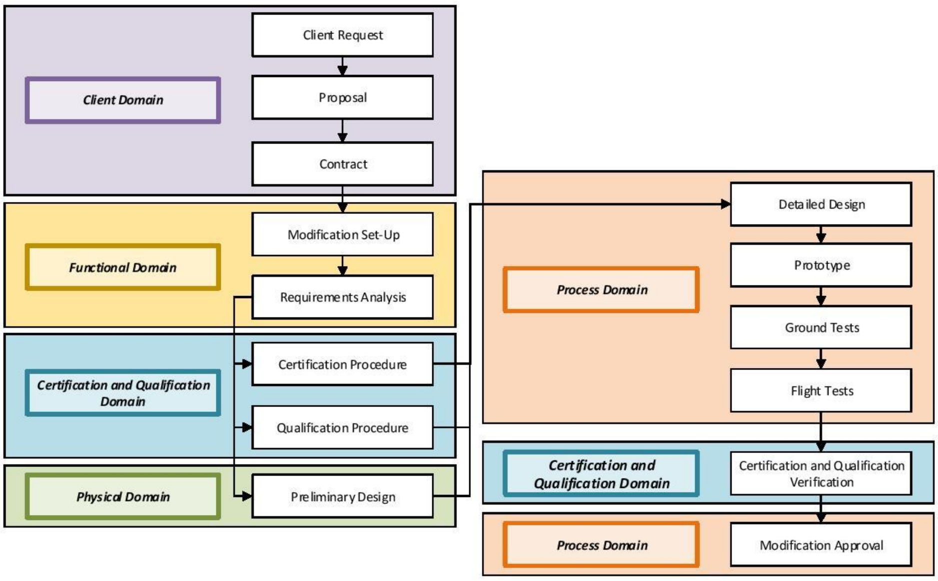


Fig. 3-2 - Modification Design divided in several domains

The nature of this particular project and this particular field of engineering requires the consideration of an extra domain, regarding Certification and Qualification process which isn't referred in Axiomatic Design methodology. The steps that are part of this domain occur in a parallel time significance with the physical domain.

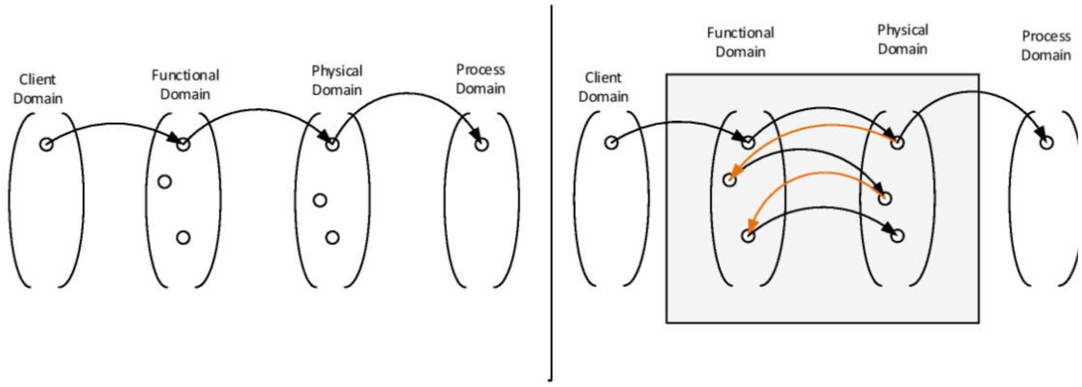


Fig. 3-3 - Difference between interaction among different domains in Axiomatic Design and the project in study

Naturally, a certain domain represents a set of tasks regarding to a specific nature. Following is explained each domain principles:

Client Domain

First contact with the client is established with the purpose to determine the costumer overall needs (in this particular case, a turret) and to settle the contractual agreement.

Client Request - beginning with initial meetings; defining future negotiation dates (meeting schedule) and fundamental objectives of the modification project. Definition by the client of the aircraft model to be customized. If the client does not has yet a specific turret model to be installed, one will be suggested by the design team.

Proposal - negotiation about the first outline of the project to the client, its general steps and the raw order price (modification project minimum and the maximum budget limits).

Contract - purpose of making the project official. A scope of work is defined to establish main milestones and the predicted overall project time.

Functional Domain

What does turret has to perform? It's main functionalities, requirements and main cautions to take in account.

Modification Set-Up - The modification process begins with a project team assignment. The custom procedures involve the verification of previous projects of this nature made on the aircraft model. A minute must be elaborated about a detailed reason, description of change, and the main concerns to be accounted.

Requirements Analysis - estimating the needed requirements for the outcome project. Those requirements are of various natures as contractual, regulatory, functional, operational and performance requirements which the modifications interferes with.

Certification and Qualification Domain

The aviation sector contains a strict procedure regarding to modifications, taking in account various types of procedure in accordance of a present situation followed by the monitoring of the regulator.

Certification procedure - Preparation of the change certification procedure. Activities are established in order to demonstrate the compliance with the Certification Specification in accordance to aircraft's airworthiness and other safety parameters. Appropriate means of compliance are set to justify the involved requirements.

Qualification Procedure - This section bounds to classify and certify client requirements other than relative to airworthiness. Taking as an example a client requirement of a specific exterior airplane painting or relative.

Certification and Qualification Validation Verification - An assurance of the certification is made. Follows the action of confirming if the certification status still complies with the established certification.

As can be observed, there is a recurrence to the Certification and Qualification Domain during the procedure of the Process Domain, specifically between the Flight Tests and the Modification Approval. That once more implies the not so sequential behaviour of this project.

Physical Domain

First steps toward solution development. At this point, most of the decisive steps are to be made with the interaction of Functional Domain as is seen forward.

Preliminary Design - Preliminary development of the modification. Location feasibility analysis of turret installation on aircraft. Location installation selection. Generating of various solutions for support structure. One solution is chosen to be the most viable. Geometry and physical requirements are tested in order to verify the previously established CS requirements.

Process Domain

Comes the detailed development, decisive tests and the needed specification for the modification action.

Detailed Design - Begins the creation of the necessary documentation in order to actually perform the modification. The following documentation includes models and installation drawings, material, product and process specifications. The necessary procedures and reports are also developed in this step.

Prototype - Materialising the solution. A procedure is made for the prototype to be subject for the future tests.

Ground Tests - Performing the required ground tests (if applicable).

Flight Tests - Performing the required flight tests (if applicable).

Modification Approval - Follows the final steps of modification procedure. A final approval of the client is expected. All the needed operational, maintenance and regulation documentation are presented to the involved entities in the project.

From the descriptions that were made above about the different domain contained in the Modification Plan, it may not be clear to acknowledge the complexity and the scope of each step. The time length of this thesis cannot cover in detail all the domains, and so, it is necessary to focus on a particular area of the Modification Project. Thus, this study will cover in detail the Preliminary Design, part of Physical Domain. Nevertheless, to completely understand the Preliminary Domain, it is yet necessary to understand and explore the Functional, Physical, Certification and Qualification domains.

The Fig. 3-4, is a close-up of Fig. 3-1, highlighting the Functional (yellow), Physical (green) and Certification and Qualification (blue) domains showing some of compound steps. This figure contains the second tier of detail of Fig. 3-1 and as shown, some of these steps result in an output documentation. The whole of outputs from a domain can result in an important milestone. This milestone sets if the objectives of the process during this domain are achieved, resulting in the fact that all of the requirements are met to proceed to the next step. Beginning with the more detailed view of procedure in the following domains:

Functional Domain

Team Assignment - this step settles the decision of the team that will be responsible for the project. A document must result with the team names.

Purpose of Change Statement - a creation of an abstract to justify, state the main reasons and proceeding the modification to be made.

Detailed Requirements Analysis - the action of gathering the different types of requirements to be met in this project. At this point, the list of requirements that is the output in this step are not definitive and the future meeting with the client may establish new requirements.

System Requirements Review - marked as the milestone of the Functional Domain. This may not be necessary in some projects where the initial requirements are well established on the Detailed Requirements Analysis. This milestone concerns such topics as qualification and client requirements.

Certification and Qualification Domain

Change Classification - in a civilian type modification, a checklist (referred by the regulator) is completed in order to verify that the modification is Major. (significant/non-significant/substantial). As referred before, in case of a military type modification, the change classification and approval can be done entirely by an DOA entity.

Application for Major Change - In cases of a civil type modification, the checklist filled in the previous step is presented to the regulator. In case of a military or state type modification, this step is not necessary. Follows the filling of the EASA form FO.TCHH.0031

Establish Certification Plan - The Change description is defined; Certification Basis, Program Schedule and respective responsibilities. Certification Basis is a sub-document which defined the Certification Specification (CS) to be evaluated in this modification (CS-25 in this particular case), among other types of protection requirements. The complexity of the specific modification may involve the collaboration of a Type Certificate Holder (which is usually the regulator). The result of this step is the Certification Plan document, which may be updated along the process.

Establish Certification Compliance Matrix (CCM) - Once the CS document is defined (in this case CS-25) comes the time to define specifically the requirements applicable to this modification and the respective means of compliance. Means of compliance are a set of 8 types of justification of a requirement. The different MC (Means of Compliance) are the following[22]:

MC0 - Compliance Statement: rationalization and allusion based on previous and/or existing similar modifications on the market.

MC1 - Design Review: justification based on drawing and data provided by the Type Certificate Holder.

MC2 - Calculation/Analysis: implication of use of structural, fatigue and other types of analysis.

MC3 - Safety Assessment: associating methods like Fault Tree Analysis (deductive procedure used to determine the various combinations of hardware, software and human failures that could cause undesired consequences [23]) among other failure predicting methods.

MC5/MC6 - Ground Tests/Flight Test: Functional tests performed on the ground/air with possible electromagnetic interference tests to be performed.

MC7 - Inspection by Specialist: only performed by a Compliance Verification Engineer in case of a mandatory visual confirmation of the modification quality result.

MC9 - Equipment Qualification: common certification of used equipment on the given modification by the recognition of one of 3 document types: Technical Standard Order (TSO), European Technical Standard Order (ETSO) and Parts Manufacturer Approval (PMA).

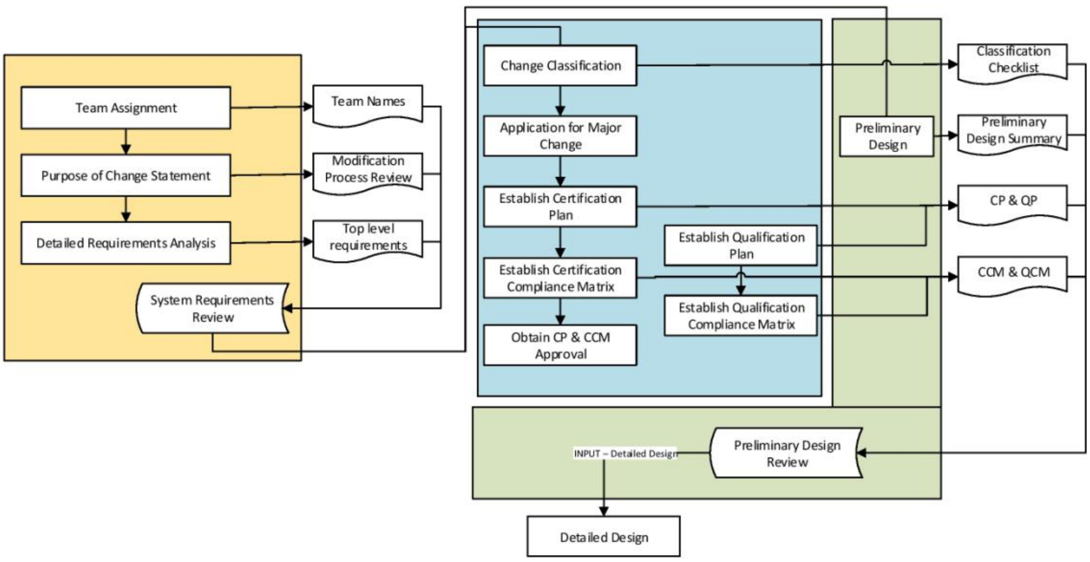


Fig. 3-4 Interaction between Functional, Certification and Physical domains

Means of Compliance 4 (Laboratory Tests) and 8 (Simulation) are not considered in this project as they are not currently used by the DOA entity.

Physical Domain

Preliminary Design - Specified steps in Fig. 3-5.

Preliminary Design Review - Documentation of the final support structure. At this point, the developed solution has already fulfilled the requirements stated in CCM and ready for further test procedure and production development specification.

As referred, Fig. 3-4shows the interaction between Functional, Certification and Qualification and Physical domains, being this last two interconnected in a parallel set in order to generate the expected outputs. As an example of this kind of interaction, the CCM is one of the most important documents for this particular study. It will expose the most critical requirements to be verified (consulting CS 25 Am. 16) and how can they be justified (M.O.C). As verified in the following chapters, once the resulting CCM is settled, the requirements that can be justified by MC 2 will be subject to the validation.

Following the analysis of a Modification Project Overview, comes the part that is the main focus of this study, Preliminary Design as a part of Physical Domain. It can be assured that one of the main objectives of this work is to design a proper methodology for this important step. The correct methodology in Preliminary Design can help to capacitate the working team to choose the right decision along with the lowest amount of time and cost. This first approach to the methodology of Preliminary Design, presented in Fig. 3-5, presents the main predicted steps and the respective outputs in this phase of the Modification Project. The further development of a case study will present a more technically detailed approach to the Preliminary Design.

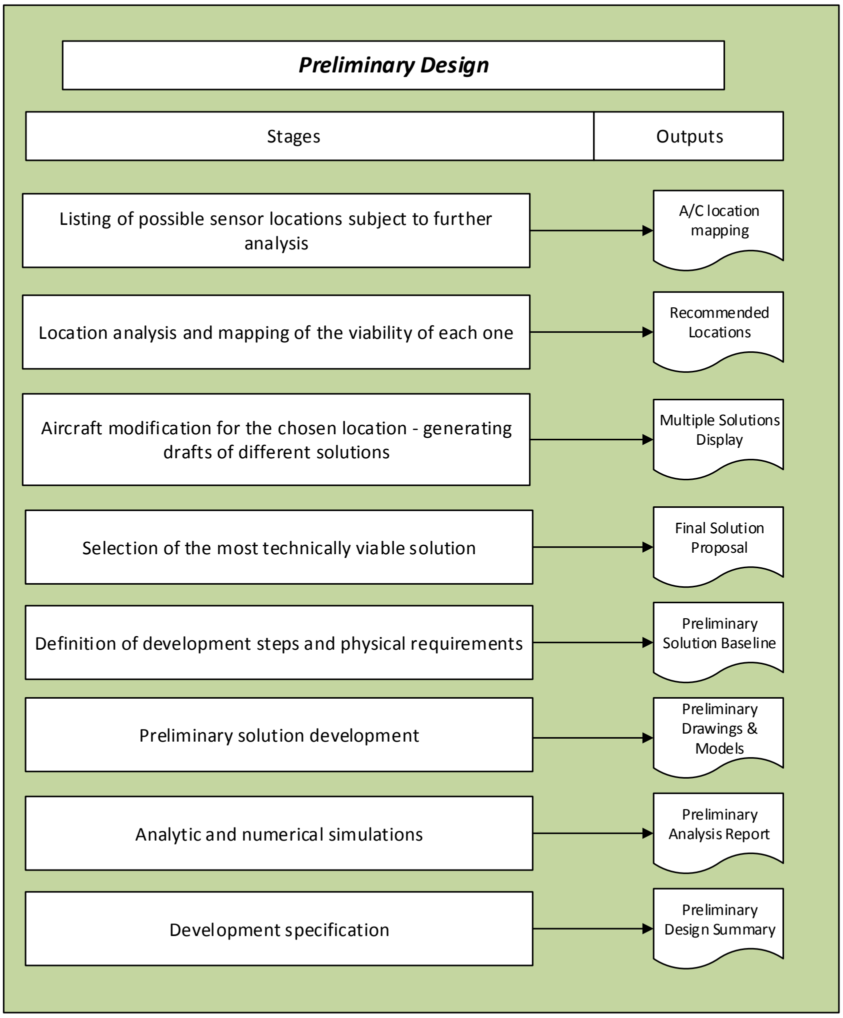


Fig. 3-5 First approach to the methodology of Preliminar Analysis

4 Feasibility analysis of turret integration on different aircraft locations

4.1 Aircraft characteristics and locations

With a length of 29.78 m, height of 11,65 m and a wingspread of 40,41 m [24], the four-engine turboprop C-130H is a part of the C-130 family which is one of most popular cargo and ground support aircrafts in the military sector to this day, servicing more than 65 operators worldwide [4]. On the Fig. 4-1, a U.S. Air Force C-130H is shown.

Fig. 4-1 LOCKHEED MARTIN C-130H during landing [4].

At preliminary analysis, the aircraft itself gives the impression of a great availability and liberty in choosing a location to integrate the system. However, the process itself reveals to be far more complex. Consulting several maintenance manuals, structural repair manuals and a IPB of the aircraft, the integration of the sensor turret reveals itself dependent on several criteria, varying the viability of these in accordance with a given area of the airplane. Thus, the solution lies in dividing the aircraft's body in 17 areas and analyze each area individually and independently. Following, a representation of the respective segmentation can be consulted in [Appendix A].

4.2 Selection criteria and respective tiers of significance

In the process of selection of the optimal location on the aircraft to install a sensor turret, urges the need to create a selection and validation process in order to apply this method in any airplane model and any sensor turret model, regarding only to their respective characteristics. During the selection of the necessary and sufficient criteria, it is necessary obtain a result where all the criteria selected are in fact independent of one another and in case they are not, what is their magnitude of importance and interrelation. The final criteria which should be considered for the selection of the optimal location are the following:

1. **Sensor´s sight range -** It was determined as one of the major criterion for the system. From an operational point of view, it is mandatory that the sensor operates within its total range of sight capabilities.
2. **Interference with other parts -** This criterion includes every kind of interference that may occur. It was considered to be high priority since one must analyse:
   - Antennas (distance);
   - Vibrations induced on other parts;
   - Influence in airflow;
   - Contact with other components;
   - Internal geometry (structural interferences);
3. **Possible damage to the sensor -** Possible damage to the sensor implies a shortage to the device´s longevity, which creates the need for regular maintenance. Implies that the modification lose its purpose in a client´s point of view.
4. **Pressurized areas of the aircraft -** Delimitates the implementation in pressurized areas by the need of an additional external structure in these areas. Preference given to the non pressurized areas of the aircraft by the simplicity of integration.
5. **Sensor's Characteristics:**
   - A - **Aerodynamic impact -** can be responsible for certain change in the performance characteristics of the aircraft. Although it is not a mandatory factor, in can rule out some options.
   - B - **Structural impact -** can dictate the magnitude of the structural support system for the turret. Its characteristics can be troubling in cases where the size of the implementation becomes critical.

6. **Structure´s integrity -** in a first approach to the issue, one must consider the fragility of the aircraft's local structure since it gives an approximate idea of how difficult the modification is.
7. **Modification complexity -** criterion that regards to the eventual cost and size of the whole process of the modification. It is a gathering of the most important issues taken in the consideration for the choice of the location.

Once the essential criteria are defined, it is important to analyse how each of this criteria will affect the decision, in what way, and if there is an consideration priority of their usage. As an example, should the criterion 7 be studied before criterion 1? Is criterion 6 deterrent in considering some locations as viable? The first issue to consider is the magnitude of importance of each criterion in a relative scale of comparison. Thus, these 8 criteria are divided in 3 groups with different importance value on the selection process.

The first group and the most important, is a whole of criteria that are critical to the process. By these means, this criteria preclude any type of consideration if one of them is violated. Penurious sight range in a certain location, for example, is a clear indicator that the sensor cannot be considered on installation in that particular area, otherwise, the purpose of its installation is corrupted. Thus, the criterion 1 is constituent of the first group of importance. This aircraft´s model in study, as well as any other existing models, has a complex structure with numerous external and internal components. Some of these components are of extreme importance. Their relocation or considering a respective contact or proximity to the turret can be prohibitive, thus it is important to verify and assure that the installation of the turret in a specific location does not interfere with the correct functioning of other components vital to the aircraft's operability. So, the criterion 2 is also to be considered in the first group of importance. The last criterion to be considered for this group of the higher importance is the possible damage that a turret may suffer in being located in certain areas of the aircraft. Limiting turret´s life cycle is not a viable option by placing it in a location that can induce a high probability in collision with rocks or a vibration that causes severe fatigue to the turret's structure, taking these factors example.

Considering the second group of importance, the criteria constituent of this group are not of prohibitive nature, but can very well restrain the selection decision. The criteria 4 can induce an increase in overall modification complexity due to the importance of preserving a pressurized area, but although this criterion delimits in some important way the nature of the modification, it is almost a suggestive type criterion. 5A and 5B criteria are relative to sensor's characteristics. It is plain to verify that if various models of sensors are to be considered, with various geometry, dimensions and weight for a given location, at some point, some considered models become deteriorative to aircraft´s operation stability and performance in either aerodynamic or structural way due to sensor's specifications. Thus, this criterion must be taken in account with a due importance.

Looking at the not yet considered criteria, 6 and 7, urges the need to interpret their importance. An aircraft´s structural integrity is not linear. It can be greater in some areas then in other due to the local stresses or applied forces. Thus, combining the possibility of a turret installation with the structural integrity factor results in a decision of how to proceed to the next step and the needed requirements. Not being decisive or restraining, this criterion hampers some decisions to be made. Last but not least, the criterion 7 can be understood as an aggregation of all the decisions made in other criterions considered previously. This criterion is without any doubt, the least important factor to be considered in this selection process. Below, is presented the summary of the division in 3 respective tiers of importance:

Tier 1 - Criteria that preclude the location's viability:

1 - Sensor's sight range;

2 - Interference with other parts;

3 - Possible damage to the sensor;

Tier 2 - Criteria that restrain the location´s viability:

4 - Pressurized area of the aircraft;

5A - Sensor's characteristics - aerodynamic impact;

5B - Sensor´s characteristics - structural impact;

Tier 3 - Criteria that hamper the location´s viability:

6 - Structure´s integrity;

7 - Modification's complexity;

4.3 Criteria interdependence

Considering the tiers of criteria importance as defined, urges the need to understand how independent these criteria are. Does the consideration of criterion 1 affect directly the decision on criterion 2? And if the answer to this question is positive, is that a good thing? One of the best ways to track the independence between these criteria is to call on Design Structural Matrix (DSM). DSM is known as a management tool that enables to visualize and analyse the dependencies among the entities of any system and derivative suggestions for the improvement or synthesis of a system[25]. In this study, DSM serves the purpose of analysing the independence between criteria, which is a desirable outcome.

The dependency between a group of criteria is not a positive factor to be accounted. The purpose of the existence of a certain amount of the criteria in a decision making is to enclosure all the possible scenario that this decision may affect. Thus, it is important that two different criteria do not take in account the same scenario, or else, the change of circumstances of a given scenario affect two or more criteria, which isn´t effective. That is why it is important to guarantee that the location criteria are independent or at least just have one-way dependency. The DSM for this study is set up as follows. It can be verified that the only criteria that are affected by other criteria are criterion 6 and 7, which, being the least important, do not affect significantly the selection process. The DSM presented below (Table 4-1) also verifies that the segmentation in tiers is well defined.

Table 4-1 DSM of selection criteria for optimum location analysis

DSM	1	2	3	4	5A	5B	6	7
1								
2								X
3								X
4								X
5A							X	X
5B							X	X
6								X
7								

4.4 Location Viability analysis

At this point, all 17 possible turret installation locations are identified, as much as the 8 selection criteria, their tiers of importance and respective interdependence. Thus, surges the time to proceed for the selection process itself, which has a procedure as follows: each one of 17 locations is analysed in accordance with the criteria defined above. Table 4-2, defines the rating procedure of a given location with respect to a particular criterion.

Table 4-2 Location viability rating system.

	Green: the location meets the criteria
	Yellow: the location is adequable to the criteria.
	Red: The location does not meet the criteria

The following Table 4-3, is the result of the rating procedure of all of the 17 locations. The rating itself is made in accordance with the research of all the necessary information made in the company's internal documents and the aircraft's fabricant manual and maintenance guides.

The detailed analysis that led to each classification result that follows are shown in APPENDIX B. As can be verified, on bottom of every location analysis column (defined by respective identifying letters) is the number sums the total of green dots of that particular location rating. The more green dots a location has, the more suitable it is for the turret integration. In case of classifying a given location as red in accordance of a given criterion, that location is no longer valid for the modification project and so it is discarded.

Looking particularly at the criterion 2, it is possible to verify that each location is analysed with respect to existent sub-criteria. The rating that is shown on the line of criterion 2 is the one accounted for the total rating and so, it reflects the ratings made on sub-criteria. If one of sub-criteria is rated red, the criterion 2 is consequently rated red and thus, discarded. For a criterion 2 to be rated green, all of the respective sub-criterion must be rated green as a necessary condition.

As can be verified, the lines represent the considered group of criteria for this modification project. These criteria are already divided in the respective tiers. The rating procedure is made from the top line to the bottom to respect the result of DSM matrix about the need to follow a certain procedure order. It is important to mention that the criteria present in this evaluation procedure do not take in account criteria that might be addressed by the will of the costumer. Criteria like redundancy (duplication of components in electronic or mechanical equipment so that a given operation can continue following failure of a part) and possibility of a dynamic turret support system (articulated arm with retracting mechanism can be taken as an example) are to be considered if the costumer requires so.

One of the first conclusions to be made about Table 4-3 is the overall location's rating. As can be verified, the location A is the most suitable for the turret installation with 6 green dots. Following, lies location B which has 5 green dots. Locations I, Q score 4 green dots and CDGH are rated with 3 green dots. The last criterion to be considered is the location M (paratrooper door) rated with only 1 green dot. The rest of location are discarded because of a red dot rating in one of the considered criteria.

Table 4-3 Viability comparison board of various locations on the considered aircraft model.

Definition of location	Comparison board																
Possible locations	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Tier 1																	
1 Sensor's sight range	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟡	🔴	🔴	🟡	🟡
2 Interference with other parts	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🟡	🟡	🟡	🟡	🟡
2.1 Antennas (Distance)	🟡	🟢	🟢	🟢	🟡	🟡	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢
2.2 Vibrations induced on other parts	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡	🟢	🟡	🟡	🟡	🟢	🟢	🟡	🟡
2.3 Influence in air flow	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🟢	🟢	🟡
2.4 Contact with other components	🟢	🟡	🟢	🟢	🔴	🟢	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢
2.5 Internal geometry (structural interferences)	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🟢	🟡	🟡	🟡	🟡
3 Possible damage to the sensor	🟢	🟢	🟡	🟡	🔴	🔴	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟢
Tier 2																	
4 Pressurized areas of the aircraft	🟢	🟢	🟡	🟡	🟡	🟡	🟢	🟢	🟡	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟢
5A Sensor's Characteristics - Aerodynamic impact	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🔴	🔴	🟡	🟡	🟡	🟡	🟡
5B Sensor's Characteristics - Structural impact	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟢	🟡	🔴	🔴	🟡	🟢	🟢	🟢	🟢
Tier 3																	
6 Structure's integrity	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟢	🟢	🟢	🟢
7 Modification's complexity	🟢	🟡	🟡	🟡	🔴	🟢	🟡	🟡	🟢	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡
	6	*5*	*3*	*3*			*3*	*3*	*4*				*1*			*2*	*4*

4.5 Location viability conclusions

The consideration of the main candidate locations for the turret installation rise some final observations and concerns that are referred following:

Recommended locations

A - Considered the most favourable location regarding the possibility of turret damage. This location provides good visibility and the non-pressurized location is a plus. Relocation of glideslope no.1 and no.2 is required. Special attention must be given to aerodynamic impact given the proximity to the search radar.

B - The proximity to the nose landing gear system is the major cause of concern. The integration of the turret in this location requires the creation of an external geometry to involve the support structure. This location limits the turret maximum size to be installed. There are possible damage possibilities and good overall visibility

Alternative locations

C - Increased damage probability due to nose landing gear. This location is in a pressurized area, which requires the creation of an external structure.

D/G - Possible influence on AC system and APU system intake. Creation of an external geometry is required.

I - Closeness to the ground must be taken in account. This location is a compound of a great number of sensors. Minimum proximity to the turret must be considered.

P - Favourable location if redundancy criterion is to be considered (installation of two turret systems in each side of the aircraft is an example). Implies the creation of a considerable external structure which can interfere with the flow on horizontal stabilizer.

Q - Modification of a fuel tank is required. Reduction in fuel storage and consequently aircraft's operation range are factors to be considered. Also a favourable location in consideration of redundancy criterion.

Once it is settled that the location to be studied under this work is A, it is important to acknowledge what are the antennas that need to be relocated and a suggestive solution for the needed modification. Glidescope no.1 and no.2 are auxiliary landing antennas that assist the pilot on the landing procedure. If a relocation of these antennas is to be made, their most common new location becomes the location C, just in front of front landing gear. It is of extreme importance to verify that the antenna maintain their central position (BL 0) in order to perform properly.

Identification of a given location on an aircraft is usually done by aircraft station coordinate system. This system is settled by 3 coordinates which are Fuselage Station (FS), Water Line (WL) and Buttock Line (BL). The turret integration will be applied on location A, which is settled in Fuselage Station 93. The following coordinates of this location will be explored in more details in next chapters.

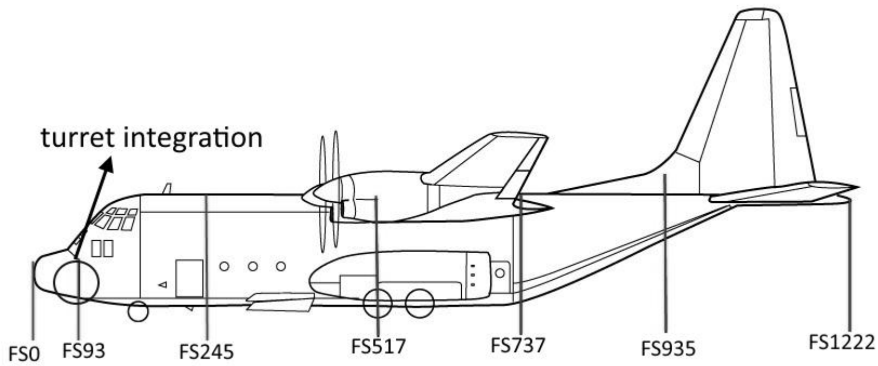


Fig. 4-2 Turret integration coordinates identification

5 State of the art: Airframe and Structural Modification.

5.1 Historical background and basic principles

In order to fully understand and follow the structural analysis procedures of the modification project in course, it is necessary to have a perception of the origin of this field of study. Historically speaking, alike the beginning of most of scientific disciplines, the origin of structural analysis happened with the gathering of various elements of knowledge, evolving from the structure discipline formation in the first half of XIX century, in France. Louis Henri Navier (1785-1836) made the first and greatest steps toward the creation of this field of study. Following him were other great minds like Karl Culman (1821-1881), James Clerk Maxwell (1831-1879) and Otto Mohr (1835 - 1918), among others [26]

Structural analysis can be understood as an attempt to describe the reality of the behaviour of a system from a structural perspective, it's boundaries and physical functionality. In its most basic definition, a structural analysis of a given system is no more than the examination of different components or elements that are a part of that particular system. Therefore urges the need to study the interdependence and relative importance of each element, loads applied on each of them and the resultant behaviour. Structural analysis can differ in its purpose, of course, with the characteristics of each system , element geometry and the desired output parameters. When performing the structural analysis one is often looking for the limits. Geometry limits to support a specific load, or the limit load to maintain the displacement below the possible danger conditions. In a practical point of view, structural analysis can be viewed as an analysis which inputs are: structural loads, geometry, boundary conditions and material properties. The expected outputs are: support reactions, local element stress and the resulting displacements.

Generally, in order to elaborate a structural analysis, one must choose between a set of possible solution approximations that attempt to explain the reality of the system behaviour. These approximations can be either experimental, analytical or numerical analysis. An experimental approach often seems to be the most logical way to perform an analysis, but not the best. The major reason of performing an experimentally derived analysis of a structure is the accuracy of its results. The use of accelerometers and extensometers provide precise data that are often considered as the absolute results of a given experiment. Analytical method has a variety of approaches including mechanics of materials and elastic theory, however it is limited to relatively simple case studies. On the other hand, numerical approach is the answer for far more complex case studies where the option of experimental analysis is just too expensive. Numerical analysis involves the consideration of models which a certain FEA software is working with. Taking as an example, ANSYS Mechanical APDL considers the Timochenko Beam Model for 1D elements.

In a direct comparison between experimental and numerical approximations, the [27] refers that FEM (Finite Element Method of numerical approximation) provides the basis for a direct analysis of complex engineering structures, however, it is generally accepted that EMA (Experimental Modal Analysis) provides more realistic description of the dynamic behaviour of the given structure. The following Fig. 5-1summarizes the comparison of the 3 alternatives in approximation of structural analysis.

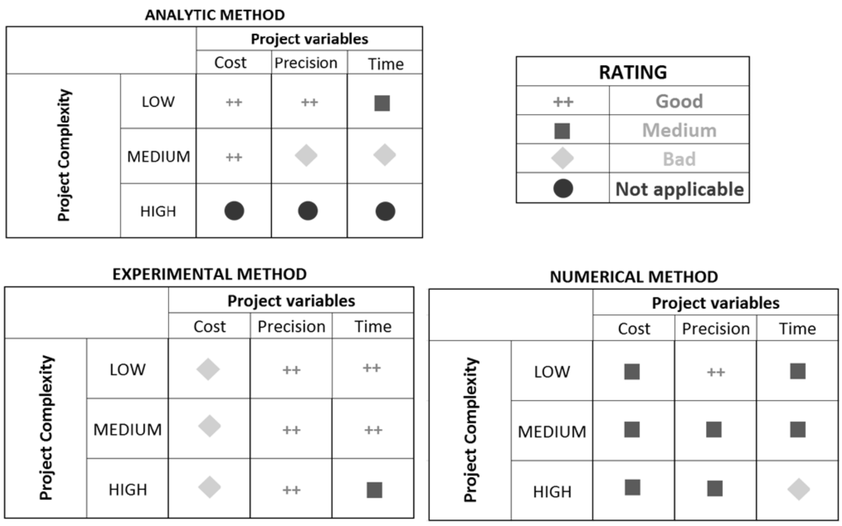


Fig. 5-1 - Comparison board of the analysis methods involving project complexity.

Considering the complexity of the following case study, analytical approach is by far a constraining option once the time required for the method and the result error approach are considerable. Of course, experimental approach to every case study is the option that will provide the most trustful results, however the costs involving this method make it unfeasible. Hence, comes the numerical method of approach, specifically Finite Element Method., which is one of approximations in the numerical analysis.

5.2 Finite Element Method

In order to deliver a proper major modification methodology (being the real purpose of the present work), one must perform a case study in order to come across all the possible outcomes. A case study is no more than the procedure of a particular problem which is relevant to the study. As for this project, the analysis of all the loads applied on the *LOCKHEED MARTIN HERCULES C-130* front fuselage section, particularly the front bulkhead, is the case study to be followed. Fig. 5-2 shows the front bulkhead of the aircraft, as a result of radome removal.

Fig. 5-2 - LOCKHEED MARTIN C-130 with the radome removed.

FEM can be simply described as an approximation to a complex problem, with a complex geometric domain, by dividing this domain into a finite number of simpler sub domains, called finite elements. The action of dividing a complex domain into smaller simpler domains is called the discretization of the domain. The process of dividing a domain into a number of finite domains and the solving of governing equations will always be matched by a numerical mesh discretization error, which is decreased with the action of increasing sub domains [28]. It is assumed that no user error or geometry simplification error is made during the procedure of case study.

After the mesh discretization, each one of the sub domains, or elements, is taken into account as an independent geometric region. Algebraic equations are developed using governing and boundary condition equations in order to describe the behaviour of the collection of these elements called finite element mesh. Physically speaking, this algebraic equations tend to describe the variables that are responsible for the respective behaviour of these connection nodes. Shared nodes result in the process of assembly of the different element properties into a global system of equations, which have the form as stated in 5.1.

F = Global applied load K = Stiffness matrix u = Primary variable	$F = K \times u$	(5.1)

As stated, the basic understanding of a FEM analysis method is the evaluation of problem variable as stress, displacement or temperature gradient in each finite element normally described by the material properties. These material properties can be thickness; coefficient of thermal expansion, density, elasticity modulus, Poisson's ratio; shear modulus, among others. From a practical point of view, one must consider the following milestones in the process of FEA analysis:

1. Defining the problem geometry (possibility of symmetry or anti-symmetry geometries).
2. Defining element type (1D, 2D or 3D);
3. Defining the material properties;
4. Meshing the geometry and evaluation of element behaviour. A mesh refinement can be required;
5. Defining boundary conditions and applied forces;
6. Post-Processor;

1 - The preliminary analysis of the geometry of a given object defined as the problem is crucial for the following steps in FEA. By analysing the geometry, one must consider possible simplifications in modelling the geometry on a FEA software. This choice can be dependent on the expected precision of the results but also depends on the user expertise to predict what simplifications will not corrupt the solution precision at all.

2 - Mostly, the easiest identification of a given element type is trough its shape. There are 3 major types of elements, 1D, 2D and 3D. 1D elements are the simplest with geometry defined by a straight or curved mid-axis line limited by 2 nodes. This 1D model is frequently used in cases of long symmetrical structure with uniform cross section. The properties of the cross section is defined through element properties. Approximation of 1D element to 3D geometry is therefore made through the modelling of a line plus a plane (which is the cross section defined by geometric properties)

2D elements are also called shell elements. Their geometry is defined by the middle axis planes and this type of elements can vary from 3 node triangular to 8 node quadrangular. 2D models are used to defined most of 3D geometric problems, being the thickness the only geometry properties added during element properties meshing. 3D elements are usually summoned to define complex geometries that cannot be defined by 2D elements, or shells. 3D models are elaborated defining all of the geometry dimensions. Mun, Rivai and Bapokutty defined very well the visual difference of element types through the study [29] which resulted in the following comparison in Fig. 5-3.

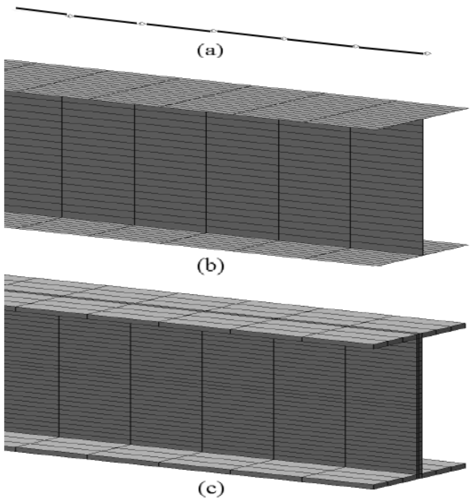


Fig. 5-3 1D model (a); 2D model (b); 3D model (c) of a I section type beam [29]

Table 5-1 shows a summarized comparison between 1D, 2D, and 3D element models.

Table 5-1 Comparison table between 1D,2D and 3D element models

	When to use	Advantages	Disadvantages
1D	Long, slender and constant cross section.	No cross sectional modelling is required. These are defined by input element properties (torsional constant; moment of inertia among others); Very low number of elements required.	Not as precise at intersection between 2 elements as 2D or 3D models. Unable of modelling plates or complex 3D geometries.
2D	Flat members where thickness is approximately 1/15 the next larger dimension. Commonly used to define 3D geometry into 2D finite element model through mid-surfacing.	Representation of 3D structure with thickness definition during the meshing. Simpler modulation and fewer elements then 3D.	Has no multiple elements through the thickness comparing with 3D modelling. Unable for complex 3D geometries.
3D	Complex 3D geometries unable to be simplified. Solid elements which must contain all of the geometric definitions of the element itself.	Only material information is to be applied to element properties. Precise data result.	Problematic in mixing different element types. Great computational power required.

Determined geometries and the regarding the possibility of simplification the modelling procedure, it is possible to analyse a problem mixing 1D and 2D elements. In fact, that is the case for this particular study, the analysis of the bulkhead which is a 3D geometry compound of long cross sectional beams and a thin plate.

3 - Material properties of the defined elements are a crucial part in order to get the wanted results. This step is where the most common failure occurs: the input of material properties with different units from those that the software is set. In order to elaborate structural analysis, it is necessary to present properties of the material such as Poisson's Ratio, Density and Elasticity Modulus, just as was referred above.

4 - The process of geometry meshing is probably one of most time expensive steps in the FEA process. Once this study will involve the interaction between 1D and 2D elements, the consideration of different aspects of each type of elements is required. For a 2D element meshing, one must consider a mesh with elements presenting an acceptable shape in order to obtain valid results. One of the main options in creating a mesh with 2D elements is selecting the element geometry (triangular or quadrangular) and element size. The software in use, *ANSYS Mechanical APDL,* presents an additional major option which allows to define whether the mesh should be created as Free of Mapped. Free meshing operation, as stated in [30], has no meshing requirements for the model geometry nor the type of elements to mesh. In other words, almost any geometry can be meshed using a combination of different geometries of elements (triangular or quadrangular). Mapped meshing option requires selected model geometries in order to be able to mesh. Thus, the selection of quadrangular elements, for example, requires a quadrilateral area to mesh.

Considering 1D meshing, the element type to be used is BEAM 188, in which the main concern is the keypoint of orientation. This keypoint is the third node (considering the already defined 2 beginning and end nodes) that must be defined in order to set the orientation of the element local coordinate system. This orientation point is relevant if the moment of inertia of a given beam changes with its orientation. With 2D elements, a similar concern is taken into account when the local coordinate system is considered. 2D element type to be used in SHELL 181.

Nowadays in Structural Analysis, the computational capability of computers allow to avoid the generation of excessively distorted elements in meshing by the generation of smaller elements. Generation of considerably smaller elements not only can answer the problem of the deformed elements but also the error decrease in the considered results. The facts presented in this paragraph has motivated the existence of the following Chapter 6.4.5. The purpose of this chapter is to verify if the detailed meshing procedure, paying attention to the defined criteria (like element geometry), is a worthy time spending procedure instead of a more quick Free meshing procedure.

Table 5-2 BEAM 188 and SHELL 181 capabilities[30]

Element Type	Capabilities	Analysis Theory
BEAM 188	Suitable for analysing slender to moderately stubby/thick beam structure. Shear deformation effects are included. Lienar (2-node) beam element in 3D with orientation point K. Six degrees of freedom at each node: translations and rotations in x,y and z directions.	Timoshenko
SHELL 181	Suitable for analyzing thin to moderately thick shell structures. The element has four nodes with six degrees of freedom at each node: translations in the x,y and z directions, and rotations about the x,y, and z-axes. Suited for linear, large rotation, and/or large strain nonlinear applications	Reissner-Mindlin

5 - The definition of all forces applied and the definition of boundary conditions are the steps that follow one method, the conservative one. The conservative method is particularly focused in the simplifying the case study in order to predict the worst case scenario. That idea follows with the idealization that if a system can resist the worst case scenario, it is possible to validate the obtained design.

6 - Final result analysis and concluding remarks. Comparison with the desired objectives is required.

5.3 Airframe breakdown

In aviation, a structure is often described as an assembly of thin, load bearing skins, frames and stiffeners. Most of the aircraft structure is composed by materials like aluminium alloys, which are lightweight and have high strength capabilities. These two properties of aluminium (as will be seen in the next sub chapter) are fundamental for an industry that seeks increasingly low weight structures with increasingly high strength capabilities. The properties of each type of structure are defined in accordance with their particular function. There are a number of different types of structures, or sub assemblies, composing an aircraft. These main sub assemblies are displayed as follows [31]:

Fuselage - represents the main body of an aircraft. Generally assembled from two or more sections and includes the pilot and the cargo compartment.

Wings - airfoils fixed to each side of the fuselage (top, middle or lower portion of the fuselage) and can vary in design. Responsible for the lifting forces and support the engines (power plant)

Empennage - attached to the fuselage. Commonly understood as the tail section. Contains operational parts that are responsible for the aircraft control. These parts are vertical stabilizer, rudder, horizontal stabilizer and elevators.

Power Plant - main responsible for the thrust delivered on the aircraft through the conversion of chemical into kinetic energy.

Landing Gear - usually retractable system essential in the landing/take off operations.

On Fig. 5-4 are shown the location of various sub assemblies on the Lockheed Martin Hercules C-130H.

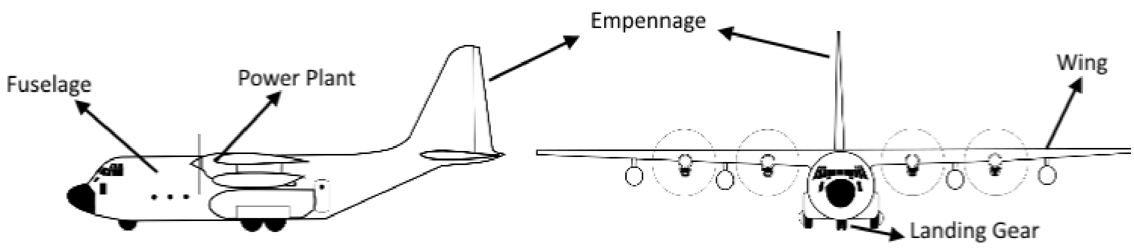


Fig. 5-4 Illustration of different sub assemblies in an aircraft.

The location for the turret integration is a part of the fuselage section (front lower fuselage to be exact). As described in [32], the main fuselage purpose is to transmit and resist the applied loads (bending, compressive and torsion). This action includes the protection of the payload/passengers from the environmental conditions encountered during the flight. The fuselage assembly must present a aerodynamic shape, resulting in a thin shell structure. The construction of the fuselage structure is itself a major topic of evolution, mainly described with 3 major designs used over the history, Truss, Monocoque and Semi-Monocoque.

Semi-Monocoque, being the fuselage design type used in modern aviation, is an reinforced version of a traditional egg shaped structure (Monocoque) but being reinforced with longitudinal stiffening members and transverse frames. This reinforcement is justified with the fact of fuselage withstanding loads such as wing reaction, tailplane reactions, inner pressure, undercarriage reactions and possible large inertia forces due to payload [32].

5.4 Aircraft structure materials

As already mentioned, the aluminium alloys are the overwhelming choice for most of sub assemblies of an aircraft. Being the priority choice for structural components of an aircraft since about 1930[33], major aluminium alloys are divided in various groups from which the most used for airframe structures construction are Group 2000 (copper as the major alloying element) and Group 7000 (zinc as the major alloying element). Group 2000 aluminium alloys are referred for cases where fatigue and damage tolerant design are critical. However, this group of aluminium alloys provide only medium strength. On the other hand, Group 7000 are characterized by their high strength capacity, but are not applicable for cases where fatigue is a critical factor.

Between the common groups used in aircraft design, the main aluminium alloys considered are 2024, 7075 and 7475. The decision of which material to use is one of the main milestones to be developed in the next chapters. For a modification project (like this particular case) is also important to consider that the material to be used must be already in use on that particular aircraft. Independently from the project, the major concerns into choosing the material are the fatigue, accidental damage, fracture toughness, creep, rupture, crack propagation rate and corrosion. The standard material procedure used in the industry is referred in [34] and by two major steps:

- Material Application - referring a minute consisting of principal loads to be applied; environment for the component, design properties among others.
- Rating Categories - rating system (0-3) of various alloys in following topics and selecting the highest ranking one:
- Static strength properties;
- Durability and damage tolerance properties;
- Producibility;
- Serviceability;

The final consideration of these steps is a subjective procedure and highly depends on the previous experience of the design team

5.5 Aircraft loads

The word "load" can, in fact, be referred as one of the most important terms in aircraft structure design and modification. When characterizing the basic principle of loads, there are two types to be considered, quasi-static and dynamic loads. Quasi-static loads refer to those applied over such a great time length that parameters like time and inertia are non relevant. On the other hand, dynamic loads can change over time as much as their centre of load. Applying the load concept in aviation, takes the need to consider different types of loads.

When talking about quasi-static loads, the different types are defined in the Table 5-3. These loads are test loads that an aircraft is subjected to when a new aircraft models is designed or a modification is made and so urges the need to verify safety levels and modify the aircraft service bulletin.

Quasi-static loads can be divided into three sections. Flight loads usually comprises loads imposed on the structure during the flight, by manoeuvres and gusts. In addition, an aircraft designed or modified for a particular role, encounters a specific set of loads during their operations. On the other hand, ground loads refer to all loads imposed on the aircraft during its movements or transportation on the ground, such as taxiing and landing loads imposed on the structure, towing, among others. Local and internal loads are understood as loads that occur either during flight or ground operations. These forces are intrinsic and always present during an aircraft life cycle.

Table 5-3 Types of quasi-static loads applied on an aircraft

Flight Loads	Ground Handling	Local and Internal Loads
Symmetric manoeuvres	Take off	**Aerodynamic Pressures**
Asymmetric manoeuvres	Landing	**Aircraft Inertia Loads**
Deep and flat spin	Taxiing (asymmetric braking, turning, etc)	**System pressures**
Gust Loads	Towing	Bay pressures
		Hydrostatic pressures
		Intake duct pressures
		Engine Thrust

When referring to dynamic loads, one must not forget to highlight the importance of the fatigue loads. These loads are cyclic loads applied on an aircraft during its operation. When performing a fatigue analysis, one must accurately foresee the stress concentration factor in order to determine a valid safe life. Important structural elements of every system subjected to cyclic loads must be replaced once a certain number of cycles is reached, that number of cycles is safe life . The fatigue analysis on its own is a complex matter which won't be approached in this study. Like in the previous table, these set of dynamic loads are a group of test loads made after a new design or major modification.

Table 5-4 Types of dynamic loads applied on an aircraft

Other Dynamic Phenomena	**Fatigue Loads**
Buffeting	Acoustic Fatigue
Dynamic Gust	Cyclic Fatigue
Modal analysis	Corrosion Fatigue
Acoustic Vibration	Thermal Fatigue
Limit cycle oscilation	
Shimmy (Undercarriage)	
Engine hammershock	

The loads that are presented in bold are the test loads that are studied within FEM analysis further in this work. As seen above, one can segregate loads from different points of view. Flight loads and Ground loads; Static Loads and Dynamic loads. Now, it is important to segregate loads into 2 other types in order to understand the reason behind the decision taken on the loads to study. When taking in account all possible loads that are applied on an aircraft, one also can see two distinctive types: external loads and internal loads. This study will be focused in specific internal loads resultant from turret integration. External loads like Aerodynamic Pressures (referred in Table 5-3) are no less important. However these set of loads is studied by a parallel project of the turret integration [1] whose output is taken into account and is further understood as Aerodynamic Pressure Forces (APF).

As already mentioned, this field of engineering requires a great amount of Certification Requirements in order to maintain the regulated safety levels. Thus, the loads that were referred just now are usually used to justify a particular set of Certification Specification (CS) Requirements. This CS Requirements are documents created by the regulator (EASA) and can vary with the aircraft type and include a requirement list for all the possible modification. As already referred, the aircraft under study, *LOCKHEED MARTIN C-130 H*, is settled in the category of large aeroplanes. Thus, the Certification Specification for this particular model will be CS-25[35].

The nature of the modification under study requires a special attention to certain chapters of CS-25, specifically subpart C (Structure) and subpart D (Design and Construction).

5.6 Structural Analysis

5.6.1 Static analysis

In order to study the outcome of applied loads on an aircraft, one must acknowledge the action of discovering these loads, through structural analysis. Structural analysis is no more than the study of effects of a load action or application. Just as the types of loads, there are Static Analysis and Dynamic Analysis, each one to analyse the respective process type.

Static analysis is the study of load effects when all the external loads applied are in static equilibrium. There are two main arteries in this type of analysis, linear and non linear static analysis. The main separation is due to material behaviour consideration. Static Linear Analysis refers to a set of assumptions like the constant magnitude of applied loads; material property in which the relation between applied stress and material strain is linear, respecting Hooke's Law; Material stiffness is not changed during the loading; non variation of initial boundary layers. Assuming that the material does not have linear behaviour (in its mechanical properties or geometry) nor the permanent load magnitude or boundaries, this nonlinearity can be caused by material behaviour, large displacements, and contact conditions. The Fig. 5-5 shows the visual difference in relation between force and deformation of each analysis type.

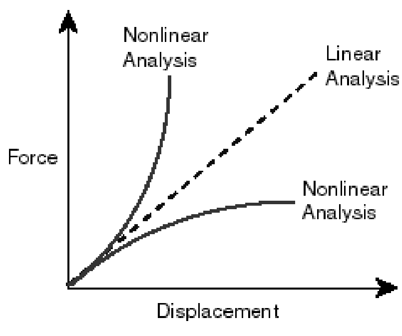


Fig. 5-5 Representation of Linear and Nonlinear Analysis relation [36].

During the static non linear analysis of ductile materials utilizing the *ANSYS Mechanical APDL*, the Maximum Distortion Energy (also known as Von Mises - Hencky) theory of failure is considered. According to this theory, a given structural material can resist the applied strength as long as the maximum value of distortion energy per volume in that material verifies to be inferior than the distortion energy per unit volume required to cause the yield of that same material[37].

Knowing that generally, a solid material can be loaded with three directions of normal stress and three directions of Shear stress, one must consider a quick, effective way in order to compare meaningfully the stress conditions to the data-base. A FEM software combines all of these 6 stress components in a single number output called Von Mises Equivalent Stress (VMES). This is obtained by:

$\sigma_{VMES} = VMES$ $\sigma_{11} = Normal\ stress$ $\sigma_{23} = Shear\ stress$	$\sigma_{VMES}{}^2 = \frac{1}{2}[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{11} - \sigma_{33})^2 + (\sigma_{23} + \sigma_{31} + \sigma_{12})^2]$	(5.2)

As stated in [38], The VMES equation computes the net energy stored by an element distortion, delivering that value as an equivalent stress. Unlike the 6 components of stress that compound VMES, this last one has no direction, only magnitude. Thus, this final value is compared with the material yield criterion, obtaining the desired yes/no comparison milestone procedure.

5.6.2 Buckling and Crippling

There are two major distinction in beam failure, material failure and structural instability (buckling and crippling). Structural instability is the cause of phenomenon as buckling and crippling. Buckling may arise in conditions of compressive stress on a beam and occurs during eccentrically loading conditions. Buckling tend to occur in conditions when the length dimension is considerably bigger than its other dimensions. This type of failure is also very dependant of the material stiffness.

Buckling is an important milestone of verification during airframe practical design and sizing and usually is taken into account in result of the comparison between numerical results and the analytically defined Critical Load. Critical Buckling Load is currently accepted by Euler formula [34] and defines the limit from which a column is stable (the system will return to its equilibrium position after the load removal) and unstable (deformation during the load is permanent or increasing). Euler formula gives acceptable results in predicting failures by lateral translation for the load of a simple pin-ended column.

P_{cr} = Critical Buckling Load; *c* = End fixity coefficient E = Modulus of Elasticity I = Moment of inertia L = Effective length	$P_{cr} = \frac{c\pi^2 EI}{L^2}$	(5.3)

For a given beam, a boundary conditions (Fig. 5-6) must be defined in order to establish the critical buckling load. At this point, definition of boundary conditions, beam geometric attributes result in definition maximum buckling load. After the numerical test procedure, the comparison defines if critical buckling conditions is achieved.

Crippling phenomena can be understood as local buckling. Not being dependant on the beam length, this failure mode usually occurs in beam webs when subjected to compressive loading .

Currently, there is no analytical method for the prediction of crippling stress. Thus, an empirical method is used in this type of analysis with the recurrence of compression yield stress as crippling strength. These empirical method have been proven to deliver satisfactory results[39]. On the Fig. 5-8, curves can be observed which relate *b/t* and *Fcc* for Channel section beams to be used in the final structure.

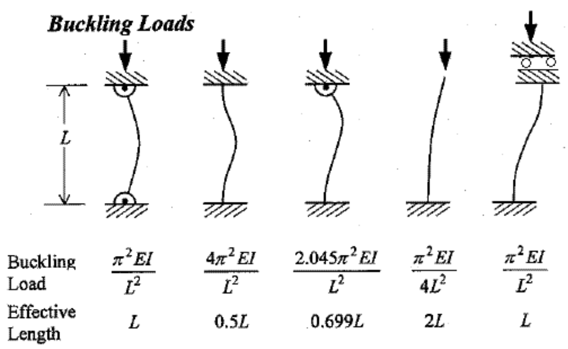


Fig. 5-6 Column end-fixity conditions [40]

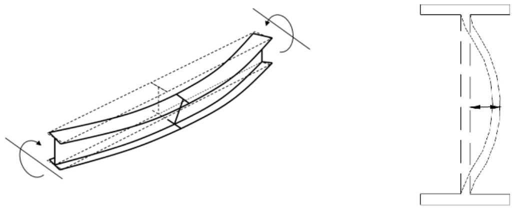


Fig. 5-7 Example of Buckling (left) and Crippling (right) phenomena of I-section beam

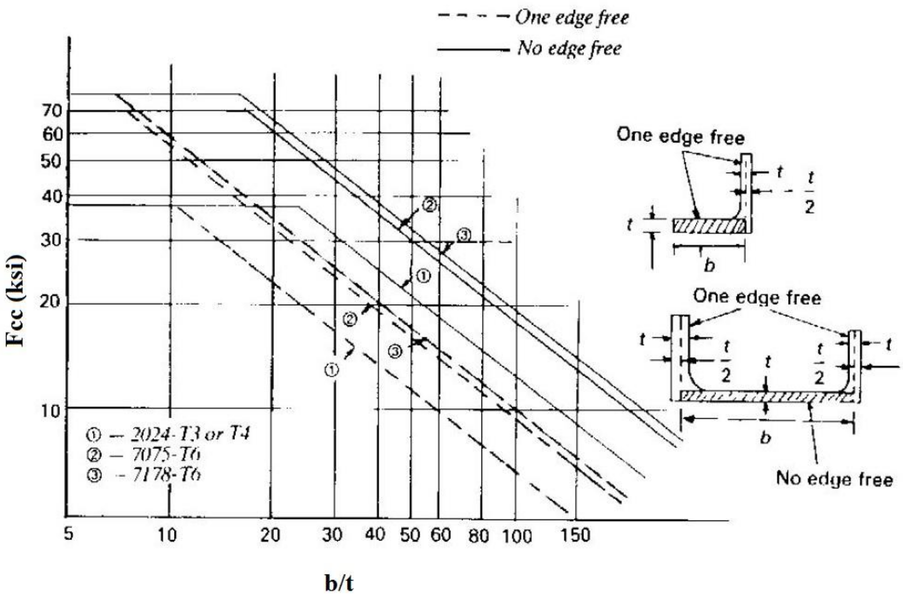


Fig. 5-8 Crippling Stress (Fcc) of aluminium extrusion alloys [39]

5.7 Weight and balance

Aircraft are designed for operation conditions within a certain flight envelope. Flight envelope establishes the maximum weight relations for different types of operations, respecting the limits of overweight take-off, manoeuvring conditions in accordance with load factors established for given aircraft model . The purpose of this chapter is to present a preventive weight and balance control of the aircraft model of this modification project. The correct prevision is desired in order to optimize load distribution and minimize moment values. Weight and balance main purpose resides in completing any information to a determined aircraft service bulletin or an operational procedure before a flight. Before take-off, pilots are made aware of these limits through the flight manual and service bulletin, establishing maximum load conditions for that particular operation.

Normally, during a modification or a significant load change (addition or removal of an item from the aircraft), a total weight change is estimated:

	$\Delta\, weight = \boldsymbol{\Sigma} weight_{added}$ - $\boldsymbol{\Sigma} weight_{removed}$	(5.4)

The post-modification aircraft weight is given by:

	$BEW_{post\ modification} = BEW_{inittial} + \Delta\, weight$	(5.5)

Basic Empty Weight (BEW) is composed of airframe structure weight, propulsion weight and the weight of airframe equipment and standard items [32]. Same is applied with change of moment (Basic Empty Moment) resultant of added or removed items with respective arm to the referential origin of the aircraft (FS 0). Change of overall aircraft weight means the position of Centre of Gravity (CG). CG position is given by:

	$CG_{DATUM} = \dfrac{moment}{weight}$	(5.6)

The location of CG in relation to the Leading Edge of mean Aerodynamic Chord arm (LEMAC) as a percentage of the Mean Aerodynamic Chord (MAC) is given by equation 5.7. Knowing that the distance between the leading and trailing edge of a wing is known as chord, it is variable along the wing with respect to its shape change. MAC, is therefore an average length of the chord, considering the length variability of the wing. LEMAC is normally understood as the distance between the aircraft nose (FS 0) and the beginning of the wing, point from which MAC is measure.

	$CG_{\%MAC} = \dfrac{(CG_{DATUM} - LEMAC)}{MAC} \times 100$	(5.7)

After verifying the CG change due to aircraft modification or a normal payload estimate, one needs to certify if the weight limits are not exceeded, thus, comes a procedure (as described in Fig. 5-9). Maximum Zero Fuel Wight (MZFW) and Maximum Take-off Weight (MTOW) are major limits for aircraft weight. MZFW is equal to Operational Empty Weight + maximum payload. Estimation of ZFW (which is compared to MZFW) is important in cases where fuel tanks are located in the wing (as the aircraft model considered in this study) which creates a positive load factor on the structure. MTOW, which is frequently fixed by structural requirements in take-off and aircraft cruise weight. MTOW is normally achieved by adding maximum fuel weight to MZFW[41].

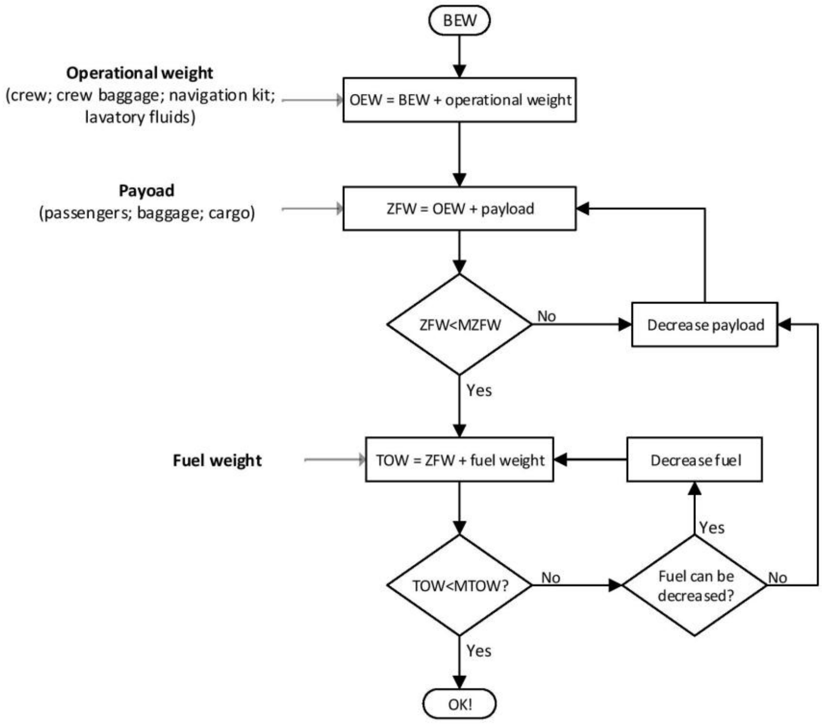


Fig. 5-9 Weight and balance verification procedure

6 Case Study: FLIR STAR SAPHIRE III integration on LOCKHEED MARTIN C-130H front bulkhead

6.1 Purpose of change

The EO/IR sensor integration will consist in the modification of the aircraft location A, also known as front lower fuselage bulkhead. The bulkhead itself is a front, flat area of the aircraft followed only by the radome shell. An observation of the Fig. 5-2 is recommended in order to establish the main area of attention.

Modification consists on attachment of external support structure for the EO/IR sensor turret and turret plate support. Also, reinforcement of the original bulkhead structure is performed in order to minimize structural deformation during service limit conditions. Although most of reinforcement done aims to minimize turret movement in order to not to jeopardize its operability.

The procedure of Case Study marks the establishment of Certification&Qualification domain outputs (CCM and QCM) and the entrance of the Modification Project into the Physical domain. Reaching the part of the project where one already know what is needed for the problem solution and what it is supposed to do, comes the time to get to know how it is suppose to look, i.e., develop the solution itself through the Preliminary Design development. Thus, the elaboration of this domain is followed by establishment of the settled Certification&Qualification requirements. The framework of this step can be observed in Fig. 3-2.

6.2 Requirements

6.2.1 Certification Requirements

At this stage of Modification Design, one already knows the modification type (Major) and the Aircraft category (Large aircraft) as highlighted in Chapter 1. Certification&Qualification procedure is marked by an analysis of the CS-25 documentation in order to define the requirements to be verified not only by structural analysis but for the whole modification process. Table 6-1 represents the CCM suggested for this project. It can be verified that the procedure of Certification&Qualification domain is not exposed in this work due to the fact that the modification of this military type aircraft follows a procedure similar to civilian aircraft modification projects. This type of Major modifications are approved only by the TC holder through a STC, thus, outputs like CCM are merely suggestive and have to be approved by the regulator entity. The lines that are filled as grey are the requirements that this study proposes to achieve.

Table 6-1 Suggestion of the Certification Compliance Matrix

Origin Document nr.	Origin Document Ver.	Reference	Tittle	System	ATA	M.O.C
CS-25	16	25,25	Weight Limits	FLIR	46	MC2: Calculaton/Analysis
CS-25	16	25,27	Centre of gravity limits	FLIR	46	MC2: Calculaton/Analysis
CS-25	16	25.301	Loads	FLIR	46	MC2: Calculaton/Analysis
CS-25	16	25.303	Factor of Safety	FLIR	46	MC0: Compliance Statement
CS-25	16	25.305	Strength and deformation	FLIR	46	MC2: Calculaton/Analysis
CS-25	16	25.307	Proof of structure (a)	FLIR	46	MC0: Compliance Statement
						MC2: Calculaton/Analysis
CS-25	16	25.321	Flight Loads	FLIR	46	MC2: Calculaton/Analysis
CS-25	16	25.471	Ground Loads: General	FLIR	46	MC2: Calculaton/Analysis
CS-25	16	25.561	Emergency Landing Conditions: General	FLIR	46	MC0: Compliance Statement
				FLIR	46	MC2: Calculaton/Analysis
CS-25	16	25.571	Damage-tolerance and fatigue evaluation of structure	FLIR	46	MC2: Calculaton/Analysis
CS-25	16	25.581	Lightning Protection	FLIR	46	MC1: Design Review
CS-25	16	25.603	Materials	FLIR	46	MC0: Compliance Statement
CS-25	16	25.609	Protection of Structure	FLIR	46	MC1: Design Review
CS-25	16	25.625	Fitting factors	FLIR	46	MC0: Compliance Statement
CS-25	16	25.681	Limit load static test	FLIR	46	MC2: Calculaton/Analysis
CS-25	16	25. 1301	Function and Installation	FLIR	46	MC6:Flight Tests
						MC5: Ground Tests on A/C
						MC9: Equipment Qualification
						MC1: Design Review
CS-25	16	25. 1529	Maintenance Manual	FLIR	46	MC0: Compliance Statement
CS-25	16	25. 1541	General - Markings and Placards	FLIR	46	MC0: Compliance Statement

25.301 - Definition of Limit Loads condition to be applied on the aircraft.

25.305 - Verification of the structure withstand utilizing 25.301 and 25.561 with respect to used materials and geometry specification

25.307 - Assure that the 25.305 can be verified through MC2 if the experience has shown it is possible. If not, experimental tests must be done to verify so.

25.561 - Definition of Ultimate Load condition to be applied on the aircraft.

25.681 - Compliance with the limit load requirements defined must be shown.

6.2.2 Qualification and other Requirements

There are no Qualification requirements to be considered for this project. Besides the Certification&Qualification requirements specified above, there are some other technical constraints that must be taken into attention:

- The support structure to be developed must permit not only the installation of the selected turret model for the project (*FLIR STAR SAPHIRE III*) but also other EO/IR sensors of the same type.
- The turret should not be subjected to vibrations inferior to 20Hz.

6.3 Failure Criteria

6.3.1 Material yield strength

The main purpose of static analysis is to evaluate the stress that a determined structure is subjected to, and thus, to ensure that the structure can safely withstand those stresses (required by CS-25). Static failure is defined by yield or rupture using the margin of safety (MS). A special factor can be applied to the margin of safety calculation according to airworthiness requirements or conservative purposes. This factor is often defined as 1,5 for conservative purposes in this industry. Thus, MS is given by:

$$MS = \frac{Allowable\ Stress}{Special\ Factor \times Applied\ Stress} - 1 \tag{5.1}$$

It is concluded that the structure can safely withstand the applied loads if MS > 0. The Criteria used for the Stress evaluation in this FEA analysis is Von Mises Stress Criteria which will be taken into account as Applied Stress. Allowable stress will be Tensile Yield Strength (even for Ultimate Conditions) as VMES Criteria only works in elastic domain. For the consideration of this Conservative Effect, Special Factor will be 1.

6.3.2 Buckling

This type of failure analysis will consist on direct comparison between analytical and numerical methods. From analytical analysis, as stated, one will consider the Euler equation 5.3.

Buckling may be caused by eccentric application of the axial load (compressive tensile strength), initial curvature of the member, transverse loading, or any combination of these conditions. This possible combination of different condition is defined as Buckling Tensile Strength for the effects of this study. Note the conservative approximation of considering the VMES as Buckling Tensile Stress. This is valid, knowing that the following condition is always verified:

$$Von\ Mises\ Equivalent\ Stress > Buckling\ Tensile\ Stress$$

Comparison between VMES and Maximum Buckling Stress will be done through a Margin of Safety, as presented below. Positive MS means that the analysed beam section do not violate any buckling consideration.

$$MS = \frac{Maximum\ Buckling\ Stress}{VMES} - 1 \qquad (6.2)$$

6.3.3 Crippling

Similarly to Buckling consideration, the conservative approximation is made:

$$Von\ Mises\ Equivalent\ Stress > Crippling\ Tensile\ Stress$$

MS consideration for Crippling will be considered as:

$$MS = \frac{Maximum\ Crippling\ Stress}{VMES} - 1 \qquad (6.3)$$

6.4 Modelling

6.4.1 Material Properties

Modelling the bulkhead assembly and all its components requires the knowledge of details and technical information which are decisive as the beam sections (next sub-chapter) and material properties. Consulting the Structural Repair Manual of the aircraft model, it was concluded that the components of the bulkhead are made of 3 main aluminium alloy types. The following materials and the respective properties are presented in the Table 6-2.Modulus of Elasticity, Poisson's Ratio and Material Density are the important material properties for the predicted FEA analysis, therefore, only these material properties will be considered. During this FEA analysis, material type will be defined as Isotropic. The use of aluminium alloys that are considered for this project is justified when they are already present in the original bulkhead.

Table 6-2 Selected Material Properties

Material	2014-T6	2024-T4	7075-T6
Modulus of Elasticity [GPa]	73.1	73.1	71.7
Poisson's Ratio	0.33	0.33	0.33
Material Density [kg/m^3]	2800	2780	2810
Tensile Yield Strength [MPa]	414	324	503
Ultimate Tensile Strength [Mpa]	483	469	572

6.4.2 Bulkhead beam Sections

For the consideration of the diverse types of beams present in the bulkhead system, one must define their respective material and section properties for the 1D element properties definition. Modelling of each section was required with some special attention to details (ex: inner radius) in order to lower the error in section properties as Area and Moment of Inertia. In total, the original bulkhead without any modification had 8 different beam sections. Those are represented in Table 6-3.

Table 6-3 Beam and Beam Section identification of the bulkhead

PARTT NO. (Document of origin)	BEAM ID (Modification Project) x length [m]	Material ID
LS1032	L08-V X 1,05	2014-T6
	L07-V X 1,05	2014-T6
	L13-V X 0,315	2014-T6
LS1463	L11-V X 0,315	2024-T4
	L12-V X 0,315	2024-T4
LS2242	L06-H X 0,315	2024-T4
LS2469	L02-C x 1,98	2024-T6
LS3254-3	L14-V x 0,725	7075-T6
	L15-V x 0,725	7075-T6
LS3224	L03-H x 1,80	2024-T4
	L05-H x 0,385	2024-T4
	L11-H x 0,385	2024-T4
	L09-H x 0,385	2024-T4
	L10-H x 0,385	2024-T4
LS3492	L17-H x 0,120	2024-T4
LS3724	L16-H x 1,20	2014-T6
LS5070	L-04H x 1,89	7075-T6
LS5154	L01-C x 3,62	7075-T6

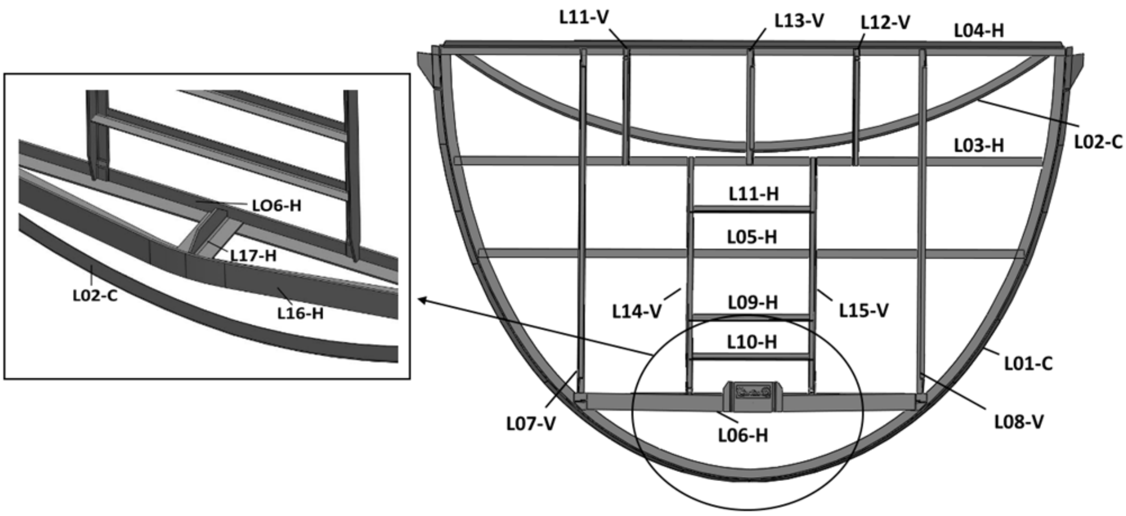


Fig. 6-1 - Bulkhead parts breakdown

Table 6-4 Beam and Beam Section identification of the Weather Radar support

BEAM SECTION ID (Document of origin)	BEAM ID (Modification Project) x length [m]	Material ID
LS2766	N01-O X 0,58	2024-T4
	N02-O X 0,58	2024-T4
	N03-O X 0,455	2024-T4
	N04-O X 0,455	2024-T4
	N07-H X 0,64	2024-T4
	N08-H X 0,64	2024-T4
	N09-H X 0,64	2024-T4
	N10-H Z 0,64	2024-T4
	N11-H X 0,695	2024-T4
	N12-H X 0,385	2024-T4
	N13-H X 0,385	2024-T4
	N14-H X 0,695	2024-T4
	N15-H X 0,745	2024-T4
	N16-H X 0,940	2024-T4
	N17-V X 0,465	2024-T4
	N18-V X 0,465	2024-T4
LS5141	N05-V X 0,465	2024-T4
	N06-V X 0,465	2024-T4

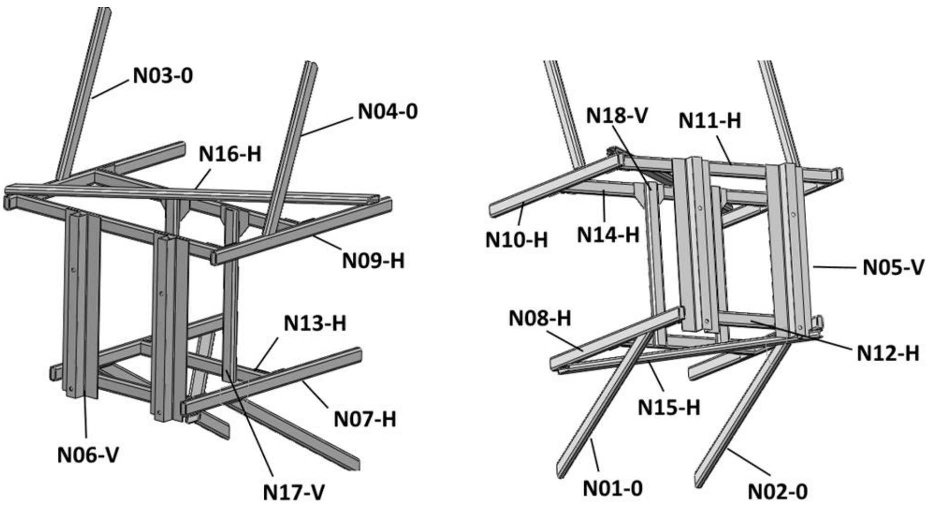


Fig. 6-2 - Weather antenna parts breakdown

6.4.3 Web

The geometric item that unites all the beams of the bulkhead is a metal panel, understood as a web. The geometry of the web is limited by beams L-04H and L-01C. Its main properties are defined by

Table 6-5 Properties of web panel.

BEAM ID	Thickness [m]	Material ID
WEB	0,0006	7075-T6

6.4.4 Geometric simplifications

Older versions of *LOCKHEED MARTIN C-130 H* radomes were compound of two circular sections which were destined for anti-icing tubes. However, the observed radomes during the project conception had those sections covered with sheet plate (Fig. 6-3 right). Thus, the geometric simplification for the bulkhead modelling omits these sections.

Front lower fuselage bulkhead is composed of both pressurized and non-pressurized areas. The analysis done in this study will not involve pressurized areas. The consideration of those involve the study of pressurization cycles (fatigue analysis) which is beyond the purposes of this analysis. The web zone characterized with red colour on the Fig. 6-3 (left) below, represents the pressurized area, therefore it will not be considered.

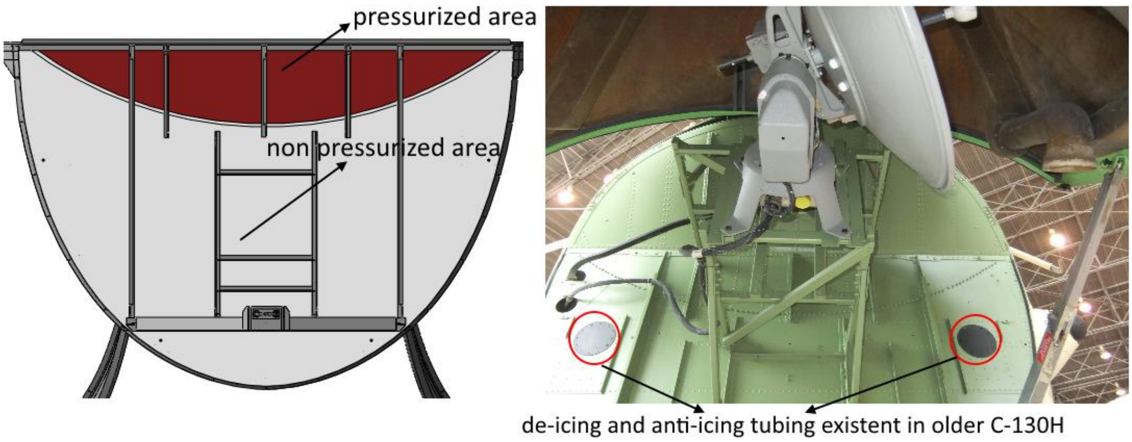


Fig. 6-3 - CAD modelling of the C-130H front fuselage bulkhead (Left); de-icing and anti-icing tubing (Right)

6.4.5 Modelling and Meshing Validation

Between the consideration of numerous details that define an accurate modelling, described in the previous chapter, one must consider what is the sufficient element number in order to present results that can be defined as realistic. Thus, came the necessity of a Meshing Validation analysis. This analysis will consist on an simulation of Ultimate Conditions Load Case 2 (see Table 6-2) without the consideration of Aerodynamic Pressure Forces (APF), on various generated models with different element length. The analysis will be done upon the original bulkhead geometry, without further modifications to be made. Thus, will be considered the Bulkhead and Weather Radar structure geometry. Regarding the consideration of the Weather Radar, one of most common models present in *LOCKHEED MARTIN C-130H* is presented in Table 6-6, being its weight important for inertial force consideration.

Table 6-6 Weather Radar Characterization

Weather Radar Model	Weight [kg]
Honeywell PRIMUS 800 RTA	9,8

On the Fig. 6-4, can be seen the simplification that was done by modelling the solution from the reality (left side of the Fig. 6-4) into FEA Pre-Processor software (right side of the Fig. 6-4). On the left side of the Fig., the orange area represents the pressurized section which, as previously stated, will not be considered for the purpose of this work. As can be seen on the Fig. 6-5, the weather radar is fixed through a plate on the structure in 4 locations. For conservative purposes, points 1 and 2 (which are ends of N03-O and N04-O, respectively) are not constrained in any way. On the left side of the Fig. 6-4, it can be seen that these beams were fixed to a pressurized area. This consideration is valid once the stress on the non pressurized area becomes higher.

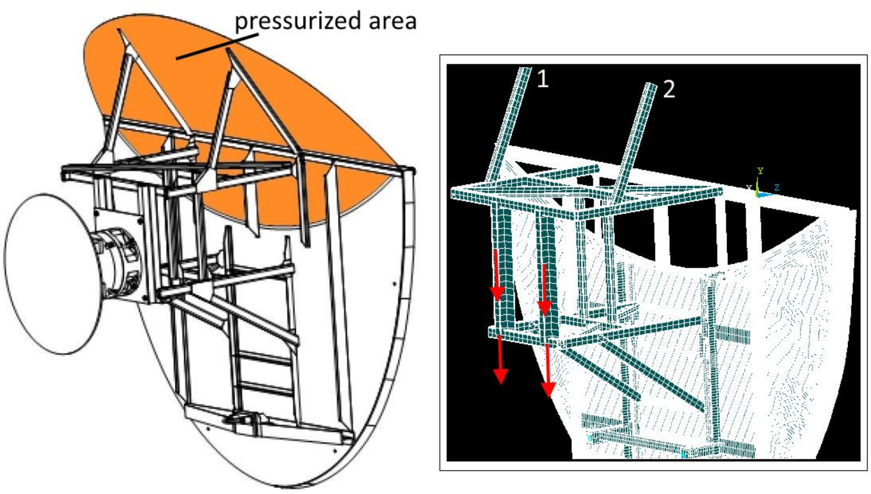


Fig. 6-4 Modelling simplification into FEA software

The purpose of this analysis is to determine the point from which the approximation error is negligible compared to the necessity of increasing the computational power (number of elements). The action of the analysis was settled by comparing the tension calculated on the same location of the geometric model (1D and 2D element), and registering the respective variation. The results for 1D elements are presented in Table 6-7, following the consideration of discretization error. Due to the absence of experimental results, in order to consider these as absolute results the solution with most elements will be considered as reference value.

Table 6-7 Relation between Element size and relative error in 1D element

Element size [m]	Element number	Tensile [MPa]	Relative Error [%]
0,05	614	4,4667	12,32137
0,025	1164	4,8242	5,303863
0,01	2841	5,0161	1,536982
0,0075	3763	5,05318	0,809124
0,006	4648	5,0699	0,48092
0,005	5604	5,0878	0,129554
0,004	7003	5,0916	0,054962
0,003	9308	5,0944	~

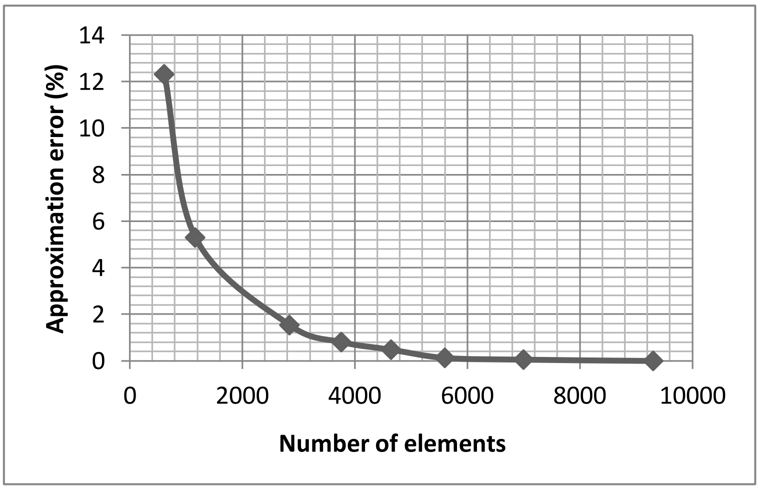


Fig. 6-5 Solution approximation error in order to element number in 1D elements type

As can be verified, the increase of global element number is followed by the increase of tensile stress in the selected 1D element. The reason behind this event is the verification of the Element Stress value. At this point, it is important to consider two distinctive ways in analysing a determined stress in Post-Process: Nodal Solution and Element Solution. Element Solution was considered for this analysis which represents the average stress value of an element. This value is really an average of given stress values coming from the nodes that belong to the element.

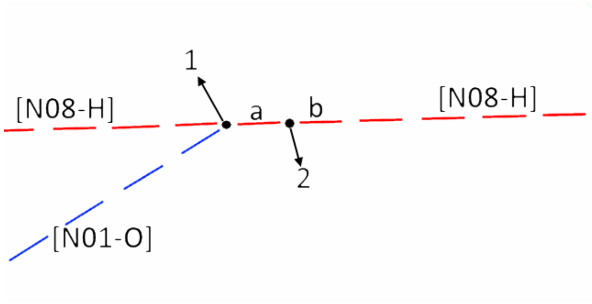


Fig. 6-6 Representation of the selected 1D element for Meshing Validation

In the figure, numbers 1 and 2 represent the nodes of the element. Letters "a "and "b" represent the elements, being "a" the selected element for this analysis. Node 1 is the local maximum stress value (joint between N01-O and N08-H). Increasing the number of elements (decrease of element size), causes the motion of node 2 closer to node 1, which increases the average stress value of the element "a". This effect attenuates once the element size (node 1 and 2 distance) is so small that the individual node stress values are similar.

Validation of 2D meshing can be verified by a similar process. Refining of the mesh is done, selecting approximately always the same element. This element is selected from the centre of the section on Fig. 6-8. As verified on the Fig. 6-8, higher stress values are verified in the upper side of this section, which is the L03-H element. Considering once more that the evaluation of tensile value was made according to Element Solution, decrease of tensile with the increase of element can be explained observing the Fig. 6-7.

The centre of the section is supposed to be an area with the lowest tensile strength. As can be observed on the Fig. 6-7, the plate with 0.05 m element length presents an element containing nodes with very different values, that is because the upper right node is located at the highest stress location and the lower left node is located at the lowest stress location. The decrease of element length and considering an element always at the centre of the plate section, causes an approximation of nodal stress values at the border of the element. Eventually, the difference between nodal stress value of an element is so little that the further the element length decrease, it causes an negligible change of element stress value. For this study, if one would select an element always at the upper right corner of the studied plate, probably an increase of stress value would be verified until the point of stagnation.

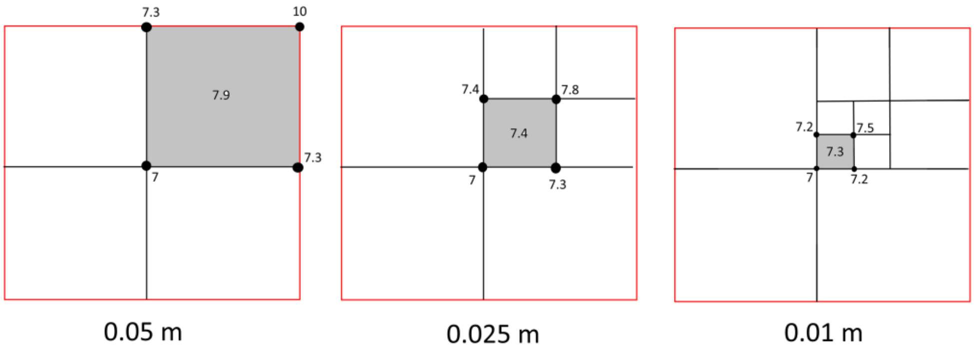


Fig. 6-7 Decrease of element tensile value with respect to element increase

Meshing validation can be also verified visually, by inspecting the evolution of medium tensile contours in 2D elements. As can be seen at Fig. 6-9, the evolution of tensile contours stabilizes in accordance with element size decrease. From 0.006 m element size, the variation in contours do not vary significantly what seems to approach to the result of difference error from there on. However, a small evolution can be observed from 0,004 m to 0,003 m which is due to change of scale done automatically by FEA software in use.

2D mesh validation result are featured in Table 6-8. Evolution of error decrease is plotted in Fig. 6-9.

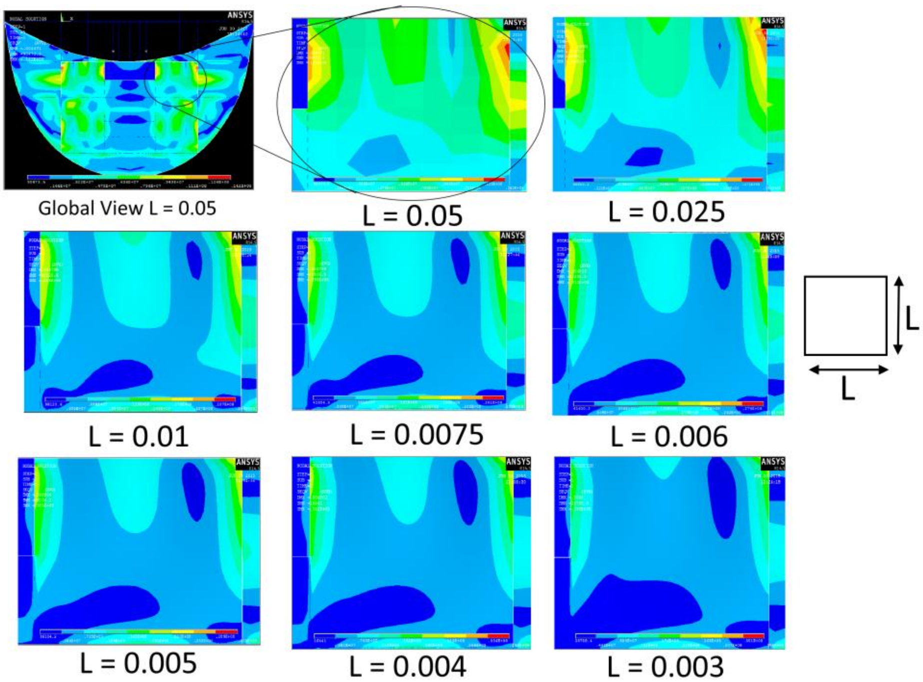


Fig. 6-8 Evolution of tensile propagation due to decrease of element size [m]

Table 6-8 Relation between element size and relative error in 2D element

Element size [m]	Element number	Tensile [MPa]	Relative Error [%]
0,05	915	7,9155	13,57669
0,025	2152	7,4012	6,197179
0,01	11710	7,3195	5,024895
0,0075	20428	7,2261	3,684732
0,006	42709	7,085	1,660138
0,005	59188	7,0102	0,58686
0,004	93546	7,0074	0,546683
0,003	164878	6,9693	~

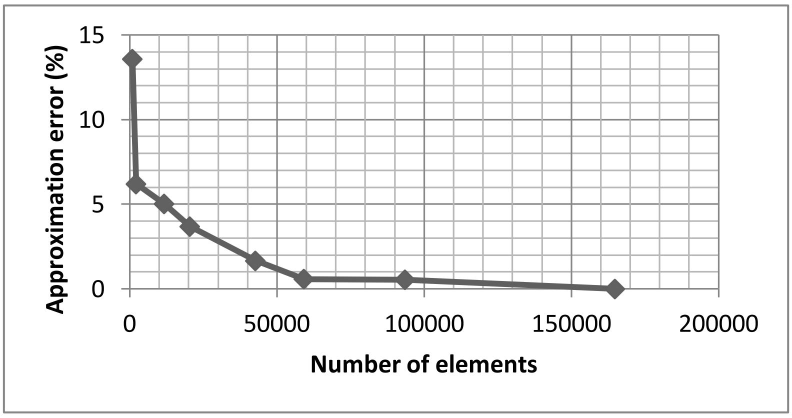


Fig. 6-9 Solution approximation error in order to element number in 2D elements type

One can also acknowledge that along with the element size decrease, the maximum global tensile value registered is constantly rising. This occurs due to the so called singularities, also known as hot spot stress points. This points tend to reveal high stress due to reduced element area. This occurrence can be explained with A(area parallel to the applied force vector) → tor) → 0 tending to zero while τ (shear stress) $= \frac{F}{A} \to \infty$.

The final solution will have 63329 elements (0D, 1D with 0.01 m element length and 2D 0.005 element length) combined, justifying this decision due to good results/computational capability relation. BEAM 188 is defined as 3-D finite strain beam, thus, the definition of each beam cross section is implies the creation of a cross section mesh. It is not known how the element size of this cross section mesh affects the results. By default, element size in cross section areas is 0.0003 m. Fig. 6-11 presents an example of a cross section mesh of beam LS3492.

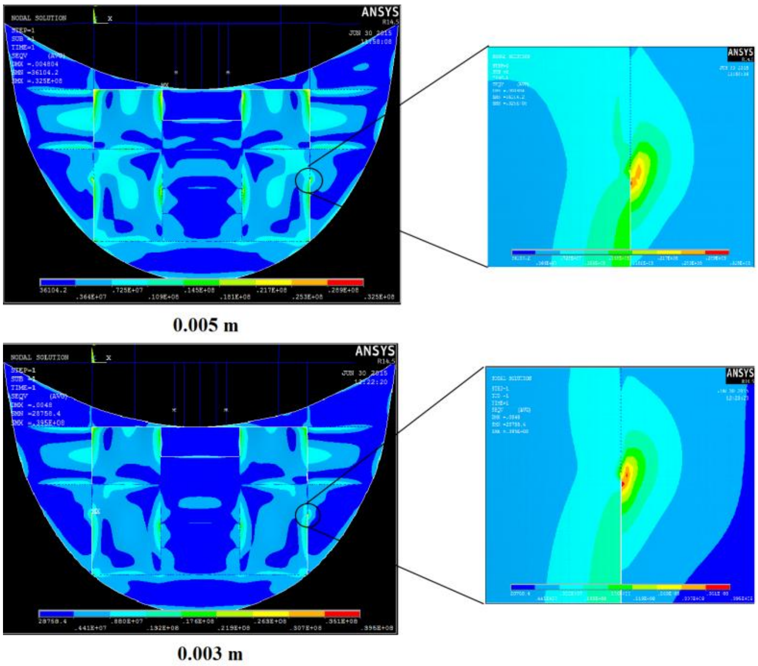


Fig. 6-10 Evidence of point of singularity in Mesh Validation Analysis.

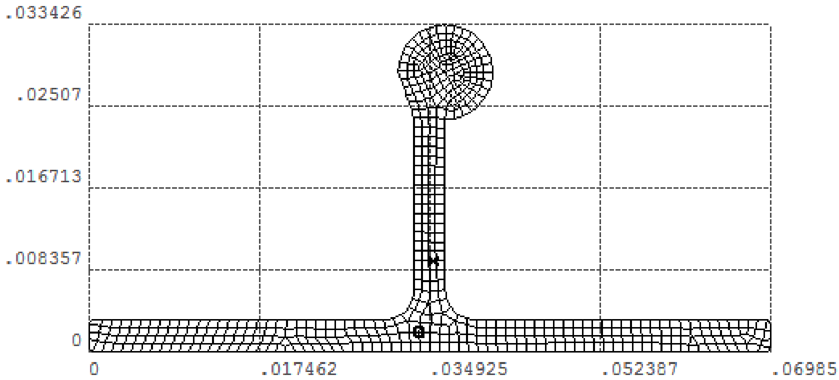


Fig. 6-11 Example of BEAM 188 cross section mesh

6.4.6 <u>Structure Development</u>

The definition of the final assembly structure can be defined as highly iterative process. Generation of various solutions, which is a part of Preliminary Design Methodology, may be one of most challenging steps in the overall process. Definition of types of beams to be used was made in accordance with two main concerns:

- Necessity of interconnection with other elements of the structure;
- Geometric section characteristics in order to sustain the applied loads.

Thus, section types as Channel (or C-beam) and L-beam were considered the most suited to be used in the construction of the final structure. C-beam is considered for structure elements where geometric characteristics is a critical factor. On the other hand, L-beams were employed in sections where the interconnection was the decisive factor. Analysis of C-channel and L-beam section types presented in the Structural Repair Manual, most suitable candidates for structure definition are presented in Table 6-9 and Table 6-10.

Structure support element identification is observed in Fig. 6-13. It is important to verify that there will be two distinct tiers of element for structure consideration.

Primary structure - critical load-bearing elements. These elements are projected to withstand ultimate conditions and are tested with ultimate tensile strength. Their main purpose is to deform but not break. If these element are severely damaged, the turret cannot operate. Primary structure elements are all except (E09-H; E10-H; E11-H; E12-H).

Secondary structure - Elements which are vital for structure deformation. These elements are present in order to reinforce the existent structure, providing a better stress distribution along the bulkhead in order to lower the final turret deformation. Secondary structure elements are (E09-H; E10-H; E11-H; E12-H).

Once the structure is developed, it is necessary to prove its integration with the radome cover and verify that no geometric boundary is violated. From the available data, it was verified that geometric boundaries are respected (Fig. 6-14)

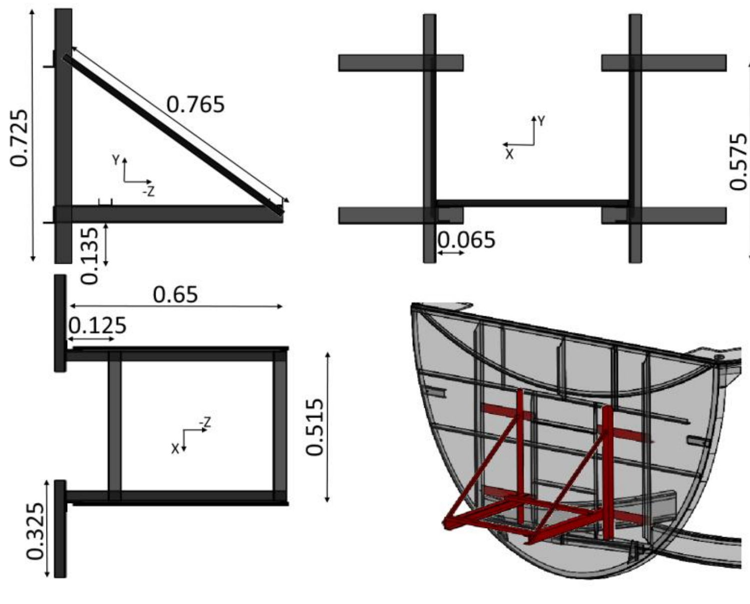


Fig. 6-12 General dimensions of the support structure [m]

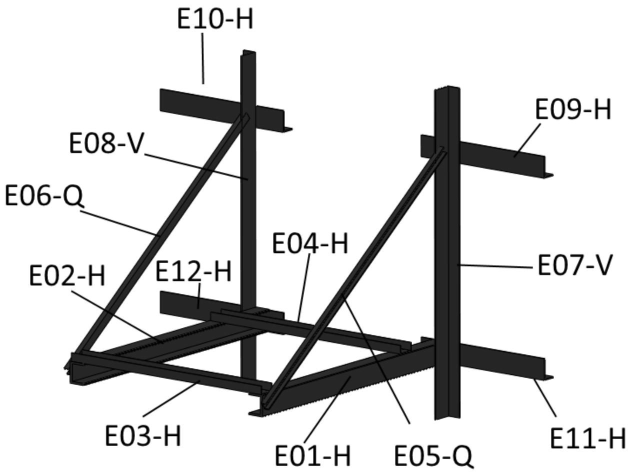


Fig. 6-13 Support structure breakdown

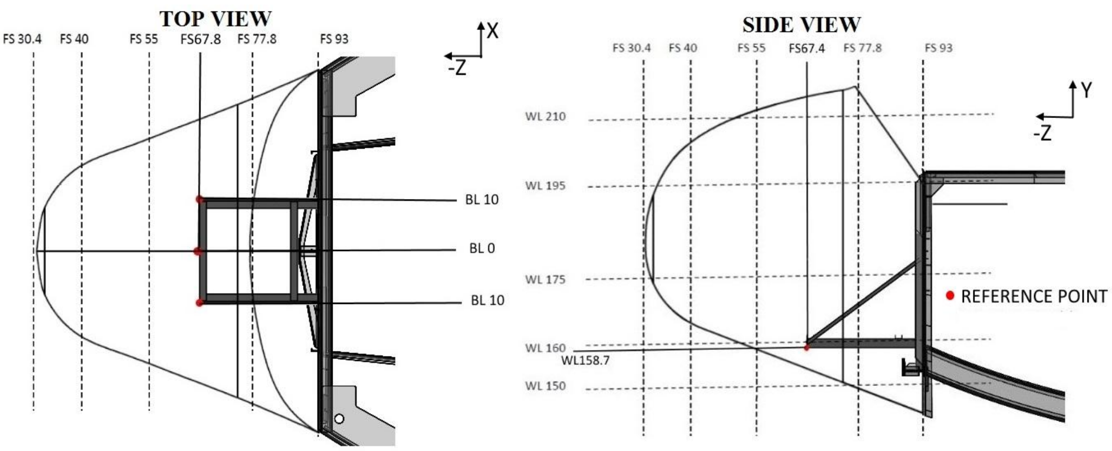


Fig. 6-14 Support Structure radome fitting

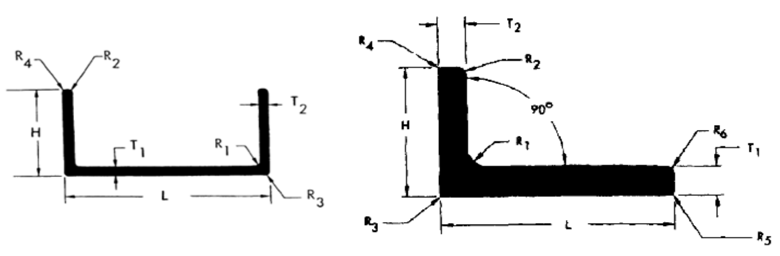


Fig. 6-15 Channel-type extruded beam characterization (left) and L-type extruded beam characterization (right).

Table 6-9 Channel beam available on Structural Repair Manual

PART NO.	L (m)	H (m)	T1 (m)	T2 (m)	R1 (m)	R2 (m)	R3 (m)	R4 (m)	MATERIAL
LS264	0,0381	0,01905	0,00157	0,00157	0,00157	0,00114	0,00114	0,00114	2024-T4
LS328	0,02858	0,02223	0,00318	0,00157	0,00157	0,00157	0,00041	0,00041	2024-T4
LS2024	0,03018	0,04369	0,00236	0,00236	0,00152	0,00041	0,00041	0,00041	2024-T4
LS2367	0,0381	0,02235	0,00236	0,0033	0,00305	0,00079	0,00079	0,00079	7075-T6
LS2430-3	0,04868	0,0381	0,00635	0,00478	0,00157	0,00157	0,00157	0,00157	7075-T6
LS2726-3	0,05077	0,0254	0,00216	0,00216	0,00102	0,00114	0,00114	0,00114	7075-T6
LS3238	0,01905	0,0127	0,00239	0,00239	0,00119	0,00119	0,00239	0,00119	2024-T4
LS3360	0,0635	0,02858	0,00318	0,00318	0,00318	0,00041	0,00157	0,00041	2024-T4
LS3360-2	0,0635	0,02858	0,00318	0,00318	0,00318	0,00041	0,00157	0,00041	7075-T6
LS3471-2	0,0508	0,0254	0,00318	0,00318	0,00318	0,00114	0,00114	0,00114	7075-T6
LS4345	0,04216	0,0254	0,00305	0,00305	0,00318	0,00079	0,00079	0,00079	7075-T6
LS4386	0,04826	0,01524	0,00152	0,00152	0,00152	0,00041	0,00041	0,00041	2024-T4
LS4436	0,03353	0,02858	0,00318	0,00318	0,00152	0,00152	0,00152	0,00152	2024-T4
LS5001	0,08255	0,03175	0,00406	0,00635	0,00239	0,00081	0,00081	0,00081	7075-T6
LS5120	0,02858	0,02223	0,00318	0,00318	0,00318	0,00318	0,00041	0,00041	7075-T6

Table 6-10 L-type beam available on Structural Repair Manual

PART NO.	L (m)	H (m)	T1 (m)	T2 (m)	R1 (m)	R2 (m)	R3 (m)	R4 (m)	R5 (m)	R6 (m)	MATERIAL
LS358	0,0528	0,04445	0,003175	0,003175	0,003175	0,003175	0,0008128	0,0004064	0,0004064	0,003175	2024-T4
ls3200-4	0,03	0,03175	0,0047752	0,0047752	0,0047752	0,003175	0,000254	0,000254	0,000254	0,003175	7075-T6
LS3206-3	0,048	0,03175	0,003175	0,003175	0,0047752	0,003175	0,001143	0,001143	0,001143	0,003175	7075-T6
LS3208-3	0,036	0,03175	0,003175	0,003175	0,0047752	0,003175	0,000254	0,000254	0,000254	0,003175	7075-T6
LS3255	0,042	0,028575	0,0016256	0,0016256	0,003175	0,0004064	0,0004064	0,0004064	0,0004064	0,0004064	2024-T4
LS3257-3	0,03	0,03175	0,0023876	0,0023876	0,0023876	0,0011938	0,000254	0,000254	0,000254	0,0011938	7075-T6
LS3378	0,036	0,03175	0,0047752	0,0047752	0,0047752	0,003175	0,0004064	0,0004064	0,0004064	0,003175	2024-T4
LS3389	0,048	0,0381	0,0047752	0,0047752	0,0047752	0,003175	0,001143	0,001143	0,001143	0,003175	2024-T4
LS3399	0,06	0,03175	0,003175	0,003175	0,0047752	0,0023876	0,001143	0,001143	0,001143	0,0023876	2024-T4
LS3919	0,09	0,03175	0,003175	0,003175	0,003175	0,0008128	0,0008128	0,0008128	0,0008128	0,0008128	7075-T6
LS4222	0,042	0,04445	0,0015748	0,0015748	0,003175	0,0004064	0,0004064	0,0004064	0,0004064	0,0004064	2024-T4
LS4302	0,11544	0,028575	0,0019812	0,0019812	0,003175	0,0008128	0,0008128	0,0008128	0,0008128	0,0008128	2024-T4
LS4439	0,051	0,0381	0,0035306	0,003175	0,003175	0,0007874	0,0007874	0,0007874	0,0007874	0,0007874	7075-T6
LS4844	0,042	0,0381	0,0023876	0,0023876	0,001524	0,0004064	0,0004064	0,0004064	0,0004064	0,0004064	2024-T4
LS5252	0,0336	0,08255	0,003175	0,0127	0,003048	0,0008128	0,0008128	0,0008128	0,0008128	0,0008128	7075-T6

6.5 Structural Loads and Boundary Conditions

6.5.1 Structural Loads

The following load cases were considered in the static analysis of loads and stress caused to aircraft structural modifications inside the aircraft. Each load case is composed by an Inertia Load and the resultant force of the aerodynamic pressure due to the turret. The appliance of structural loads will consist with two situations, Limit Conditions and Ultimate Conditions.

6.5.1.1 Limit Conditions

The appliance of Limit Conditions has as main principle in testing structural behaviour during limit operational conditions. Thus, it is important to guarantee that during these conditions of operation, yield tensile strength is not achieved and any deformation registered (in elastic dominium) is low enough so that the turret can maintain its operability with negligible effect on the resultant images.

Known as symmetric manoeuvres (see Flight Loads in Table 5-3), these are considered the limit operational conditions for an aircraft. There are four basic limit conditions [41] :

- Positive high angle of attack (PHAA);
- Positive low angle of attack (PLAA);
- Negative high angle of attack (NHAA);
- Negative low angle of attack (NLAA).

The maximum load factor to be verified in these limit conditions is the 3 G [42] load factor. The force of the aerodynamic pressure caused by these limit conditions was determined trough the "Limit Flight Speed vs Altitude Chart" which delivers the conditions for the aircraft model in analysis. At limit conditions, the aircraft experiences the following conditions:

- Altitude - 12500 feet (3810 m);
- Speed - 270 knots (≈140 m/s);
- ρ - 1,225 kg/m^3 (for conservative reasons, sea level air density is to be used);
- A - 0.152 m^2 (predicted projected area with the inclusion of turret geometry [1];
- C_D -0,6 (Drag coefficient obtained from numerical aerodynamic results [1];
- S - 1,5 (factor of safety applied to drag coefficient).

$$F = S\frac{1}{2}\rho v^2 C_D A \quad (6.4)$$

Resultant Aerodynamic Pressure Force (APF) will be of 1636 N.

Table 6-11 Limit Conditions Load Cases applied

Load Case	Description	Load Factor [G]	APF [N]
1	Upward + Aerodynamic Pressure Force	3	1636
2	Forward + Aerodynamic Pressure Force	3	1636
3	Sideward Left + Aerodynamic Pressure Force	3	1636
4	Sideward Right + Aerodynamic Pressure Force	3	1636
5	Downward + Aerodynamic Pressure Force	3	1636
6	Rearward + Aerodynamic Pressure Force	3	1636

6.5.1.2 Ultimate Conditions

Predicted in CS-25 the Ultimate Conditions are understood as the final condition of material usage in the worst case scenario, i.e., Emergency Landing Conditions [25.561] (see Table 6-12). These will define the Load Factor applied. Once again recurring to "Limit Flight Speed vs Altitude Chart" to define the APF, the conditions that the aircraft is subjected are the following:

- Altitude - 12500 feet (3810 m);
- Speed - 320 knots (≈165 m/s);
- ρ - 1,225 kg/m^3 (for conservative reasons, sea level air density is to be used);
- A - 0.152 m^2 (predicted projected area with the inclusion of turret geometry [1];
- C_D -0,6 (Drag coefficient obtained from numerical aerodynamic results [1];
- S - 1,5 (factor of safety applied to drag coefficient) .

Recurring once more to Equation 6.4, the resultant Aerodynamic Pressure Force is 2272 N. Ultimate Load Results will provide the necessary information in order to evaluate the Tensile Strength, Buckling, and Crippling stress applied. The important output will be the VMES, which is later compared to Tensile Yield Strength, Maximum Buckling Stress and Maximum Crippling Stress through Margin of Safety

Considering that the turret system is connected to the support structure by 4 locations, implies that forces caused by the turret will be transmitted to these locations. It is considered that the APF direction is horizontal (conservative manner), creating the maximum momentum. On Fig. 6-16 , W is the turret weight and APF the Aerodynamic Pressure Force.

Table 6-12 Ultimate Conditions Load Cases applied

Load Case	Description	Load Factor [G]	APF [N]
1	Upward + Aerodynamic Pressure Force	3	2272
2	Forward + Aerodynamic Pressure Force	9	2272
3	Sideward Left + Aerodynamic Pressure Force	3	2272
4	Sideward Right + Aerodynamic Pressure Force	3	2272
5	Downward + Aerodynamic Pressure Force	6	2272
6	Rearward + Aerodynamic Pressure Force	1,5	2272

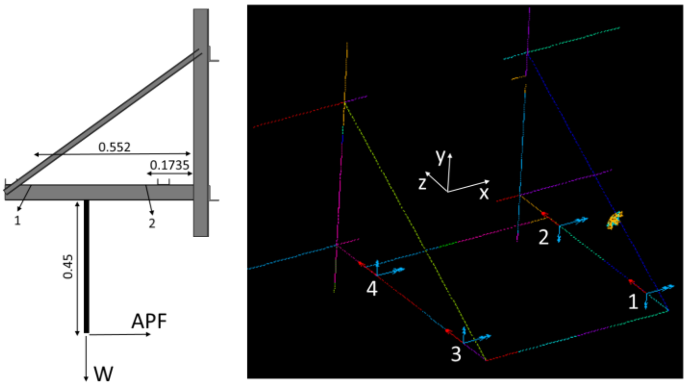


Fig. 6-16 Representation of force application locations and respective forces (right) and their geometric characteristics (left).

Efforts applied on these 4 fixation location are present in Table 6-13

Table 6-13 Applied forces on fixation points

Fixation point	Directional vector of applied forces
1	(-Fz | -Mxz | -Myz)
2	(-Fz | -Mxz | -Myz)
3	(-Fz | -Mxz | Myz)
4	(-Fz | -Mxz | Myz)

6.5.2 Boundary Conditions

After the analysis of the front lower fuselage structure, it is clear that the bulkhead has 4 major longitudinal stiffening beams which transmit the main forces along the lower part of the fuselage. Fig. 6-17 shows precisely the location of these beams both in CAD as in *Ansys*. The resulting boundary conditions will apply on these 4 locations, locking all 6 degrees of freedom (DOF) , x ,y ,z , Mx, My and Mz.

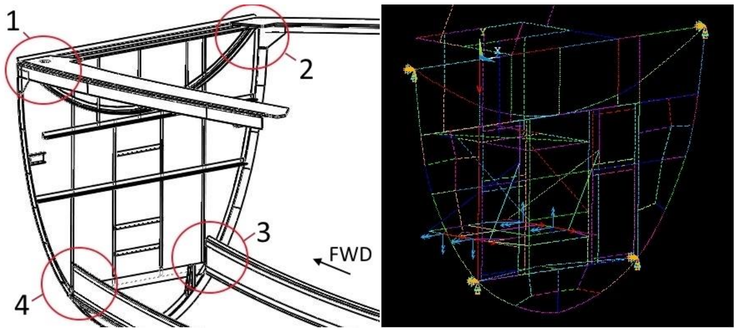


Fig. 6-17 Main longitunal support beams of lower front fuselage

6.6 Post-Process and Beam section characterization.

6.6.1 VMES, Buckling and Crippling Considerations

Foregoing the load cases and the already stated structure geometry, one must decide the beam type that suites better the load requirements. The selection procedure of channel beams will require the buckling and crippling analysis. In the APPENDIX D tables are presented with main geometric attributes, maximum buckling force (through Euler formula, presented already above) and maximum buckling tension.

Maximum buckling force obtained is due to consideration of effective length (L) = 1 (see Fig. 5-6). Consideration of this factor is due to the connection type that is predicted between different beams. In this case, connection through rivets or bolts is predicted. The consideration of connection between different structure elements through welding would increase significantly the maximum buckling force (decreasing the effective length to "0.699L"). However, the material to be used are aluminium alloys 2024-T4 and 7075-T6. These type of alloys cannot be worked with welding and thus, this connection type is not to be considered. If welding would to be considered, the beam materials to be used should be, for instance, aluminium alloys of 4000 series.

Also during channel beam selection, an empirical approximation to Crippling Stress is presented through the estimation of the Crippling force is done through the geometric ratio (as can be observed in Fig. 5-8).

6.6.2 Ultimate load conditions

Tier 1 elements section identification is considered for Ultimate Load conditions

6.6.2.1 E01-H/E02-H

Purpose - main support component of the structure and connection with the turret support plate.

Possible failure cause - Torsion due to shear stress and bending.

Beam Section - Channel (C).

Buckling and Crippling - Possible.

Table 6-14 Chosen PART NO for the E01-H/E02-H composition

PART NO. (Document of Origin)	BEAM ID (Modification Project)	MATERIAL ID	Length (m)
LS2430-3	E01-H/E02-H	7075-T6	0,65

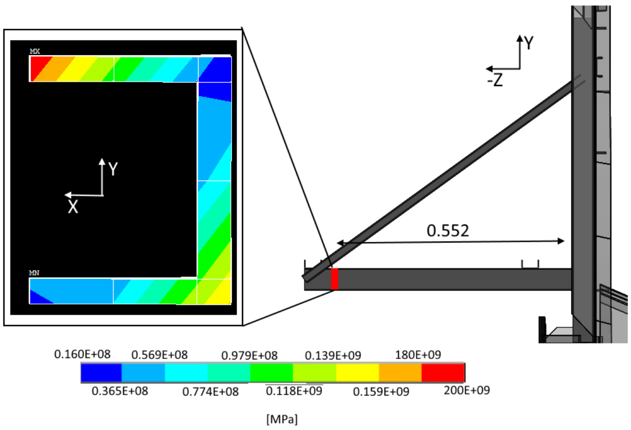


Fig. 6-18 Stress distribution of E01-H/E02-H in Load Case 1

6.6.2.2 E03-H

Purpose - horizontal support component of the structure and critical in order to prevent translation in "x" direction. Can be used for connection to turret support plate for additional support.

Possible failure cause - Bending.

Beam Section - Channel (C).

Buckling and Crippling - Possible.

Table 6-15 Chosen PART NO for the E03-H composition

PART NO. (Document of Origin)	BEAM ID (Modification Project)	MATERIAL ID	Length (m)
LS5120	E03-H	7075-T6	0,515

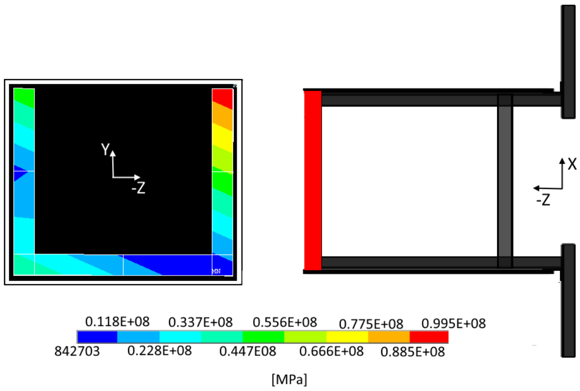


Fig. 6-19 Stress distribution of E03-H in Load Case 1

6.6.2.3 E04-H

Purpose - horizontal support component of the structure and is in order to prevent translation in "x" direction. Can be used for connection to turret support plate for additional support.

Possible failure cause - Bending

Beam Section - Channel (C).

Buckling and Crippling - Possible.

Table 6-16 Chosen PART NO for the E04-H composition

PART NO. (Document of Origin)	BEAM ID (Modification Project)	MATERIAL ID	Length (m)
LS264	E04-H	2024-T4	0,515

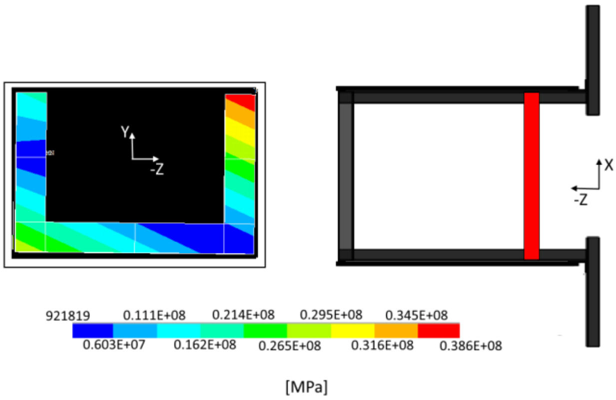


Fig. 6-20 Stress distribution of E04-H in Load Case 1

6.6.2.4 E05-Q/E06-Q

Purpose - Provide additional support to E01-H/E02-H. Minimize vertical deformation (in y) in order to deliver proper sensor operability conditions.

Possible failure cause - Axial Stress

Beam Section - Channel (C).

Buckling and Crippling - Possible.

Table 6-17 Chosen PART NO for the E05-Q/E06-Q composition

PART NO. (Document of Origin)	BEAM ID (Modification Project)	MATERIAL ID	Length (m)
LS2024	E05-Q/E06-Q	2024-T4	0,765

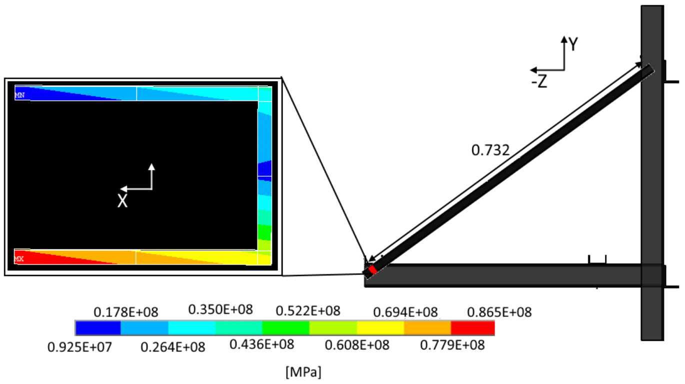


Fig. 6-21 Stress distribution of E05-Q/E06-Q in Load Case 1

6.6.2.5 E07-V/E08-V

Purpose - Reinforcement of the bulkhead. Connection with E01-H/E02-H and E05-Q/E06-Q.

Possible failure cause - Shear Stress

Beam Section - L-type.

Buckling and Crippling - Not possible.

Table 6-18 Chosen PART NO for the E017-V/E08-V composition

PART NO. (Document of Origin)	BEAM ID (Modification Project)	MATERIAL ID	Length (m)
LS3206	E03-H/E04-H	7075-T6	0,727

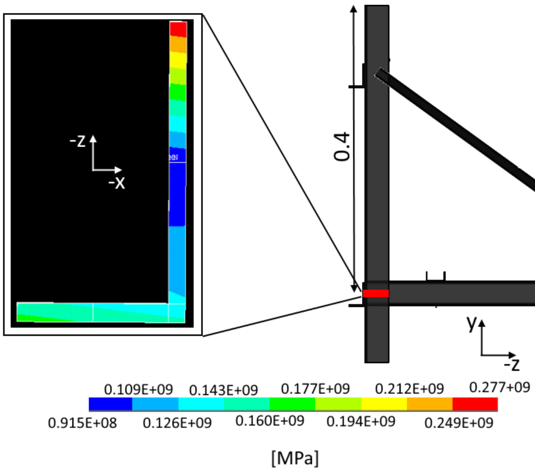


Fig. 6-22 Stress distribution of E07-V/E08-V in Load Case 5

6.6.2.6 WEB

As shown in Fig. 6-23, correct distribution of tensile strength was made in order to minimizes the stress on the sheet plate that covers the bulkhead. With an exception of an hotspot stress point, a low distribution of stress is observed. It is concluded that no reinforcement is needed during this modification.

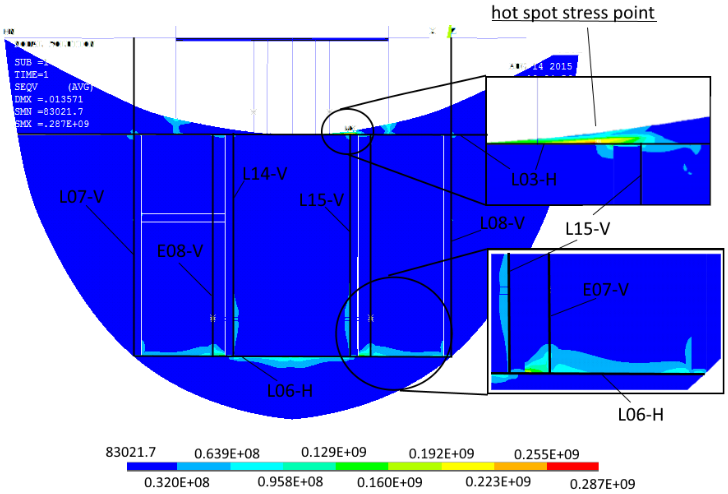


Fig. 6-23 - Web Stress distribution during Ultimate Conditions.

6.6.3 Limit load conditions

Fig. 6-24 is a demonstration of the critical locations during the limit conditions load case 5. On the right of the Fig. 6-24 deformation of the structure is shown with exaggerated magnitude in order to understand the key deformation locations. At the left of the Fig. 6-24, the same key location are specified in clearer detail.

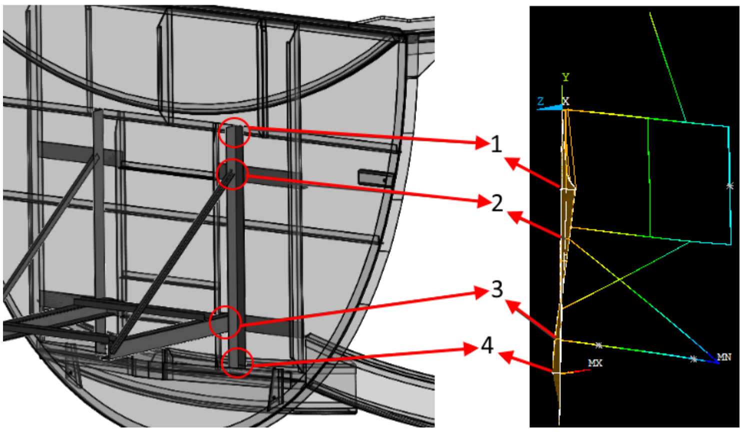


Fig. 6-24 Key structural element connections

- 1 - L03-H/E07-V interconnection (same applies for L03-H/E08-V)
- 2 - E07-V/E09-H interconnection (same applies for E08-V/E10-H)
- 3 - E07-V/ E11-H interconnection (same applies for E08-V/E12-H)
- 4 - L06H/E07-V interconnection (same applies for L06H /E08-V)

These 4, or in fact 8, locations are critical and should be reinforced in order to minimize the deformation. Thus, E09-H, E10-H, E11-H, E12-H are bulkhead reinforcement beams applied on points 2, 3 and their equivalent locations on the other side of the system. The purpose of these beams is to convey tension forces into beams L07-V/L08-V and L14-V/L15-V. Tier 2 elements beam discretization are considered for Limit Load conditions.

Table 6-19 Limit load case 5 for E09-H/E10-H/E11-H/E12-H

PART NO.	MATERIAL	Deformation point 3 in Z [m]	Deformation point 2 in Z [m]	Turret position displacement in Y [m]
LS358	2024-T4	0,002473	0,004773	0,007816
ls3200-4	7075-T6	0,002865	0,004734	0,008206
LS3206-3	7075-T6	0,002921	0,00491	0,008349
LS3208-3	7075-T6	0,002965	0,004863	0,008376
LS3255	2024-T4	0,003168	0,005254	0,008783
LS3257-3	7075-T6	0,003074	0,004939	0,008529
LS3378	2024-T4	0,002833	0,004751	0,008177
LS3389	2024-T4	0,002536	0,00472	0,007847
LS3399	2024-T4	0,002889	0,004965	0,00834

LS3919	7075-T6	0,002826	0,005128	0,008362
LS4222	2024-T4	0,002828	0,00484	0,008234
LS4302	2024-T4	0,00299	0,005526	0,008771
LS4439	7075-T6	0,002686	0,004815	0,008056
LS4844	2024-T4	0,00284	0,004836	0,008236
LS5252	7075-T6	0,00154	0,004441	0,006678

E09-H/E10-H/E11-H/E12-H:

Purpose - Reinforcement of the bulkhead. Minimize turret structure deformation in y axis. Distribution of stress through bulkhead structure

Possible failure cause - Shear Stress

Beam Section - L-type.

Buckling and Crippling - Not possible.

PART NO. (Document of Origin)	BEAM ID (Modification Project)	MATERIAL ID	Length (m)
LS4439	E09-H/E10-H/E11-H/E12-H	7075-T6	0,325

Locations 1 and 4 induce the substitution of existing beams in the bulkhead. Location 4 induces the substitution of one of the critical beams in the front lower fuselage station. A modification of this nature is too complex and not recommended, thus, this step should be considered only as a last resource. Location 1 defers to the modification of the existent L03-H beam, which is LS3224. Modification of this element is be made by the following methodology.

Assuming that the major stress applied on this beam is a shear stress, one can compare the behaviour of each L-beam candidates. This comparison can be made assuming a single shear stress passing through shear centre, therefore, not causing any additional effect Normal shear stress flow through an L-beam is represented in Fig. 6-25.

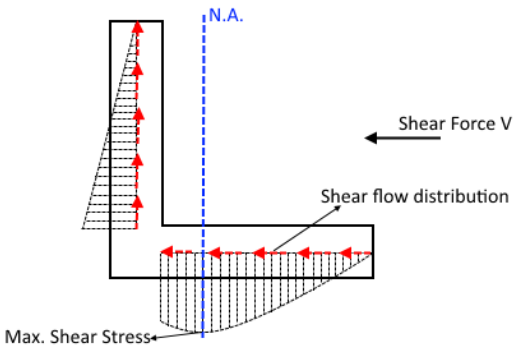


Fig. 6-25 Shear flow distribution along L-beam section

Knowing that the expression for shear stress is the following:

$\tau = shear\ stress$ $V_y = shear\ force\ along\ y$ $Q_x = First\ moment\ of\ inertia\ along\ x$ $I_x = Moment\ of\ inertia\ along\ x$ $t = thickness$	$\tau = \frac{V_y Q_x}{I_x t}$	(6.5)

Without knowing the value of V_y, one can compare the behaviour of beam candidates with respect to their geometric properties I_x, t and Q_x. This is done assuming that Q is maximum, therefore, maximum shear stress is estimated (on Neutral Axis). The relation of comparison is:

$\frac{\tau}{V_y} = Comparison\ ratio$	$\frac{\tau}{V_y} = \frac{Q_x}{I_x t}$	(6.6)

Table 6-20, represent the geometric comparison ratio of beam candidates. The smaller the value, the lower will be the shear stress (τ), and consequently, the lower will be the deformation, δ_s. This relation can be shown as:

$\delta_s = shearing\ deformation$ $G = Modulus\ of\ elasticity$	$\delta_s = \frac{\tau L}{G}$	(6.7)

Table 6-20 Comparison ratio of l-beam type beam candidates

	I (maximum) [m^4]	Centroid (along maximum I) [m]	t [m]	Q [m^3]	Comparison ratio [m^2]
LS358	9,86E-08		0,003175	0,280626	8,96E+08
ls3200-4	2,56E-08	7,29E-03	0,004775	0,20714	1,69E+09
LS3206-3	6,77E-08	1,52E-02	0,003175	0,033814	1,57E+08
LS3208-3	3,05E-08	6,80E-03	0,003175	0,023246	2,40E+08
LS3255	2,44E-08	1,33E-02	0,001626	0,029297	7,38E+08
LS3257-3	1,43E-08	7,63E-03	0,002388	0,020286	5,94E+08
LS3378	4,32E-08	9,76E-03	0,004775	0,025121	1,22E+08
LS3389	1,03E-07	1,39E-02	0,004775	0,0033542	6,82E+06

LS3399	1,25E-07	2,08E-02	0,003175	0,042945	1,08E+08
LS3919	3,77E-07	3,54E-02	0,003175	0,066134	5,53E+07
LS4222	2,73E-08	1,09E-02	0,001575	0,028075	6,53E+08
LS4302	4,57E-07	4,94E-02	0,001981	0,08626	9,53E+07
LS4439	9,13E-08	1,61E-02	0,003531	0,03584	1,11E+08
LS4844	3,84E-08	1,17E-02	0,002388	0,028638	3,12E+08
LS5252	3,87E-08	3,71E-02	0,0127	0,060628	1,23E+08

Section type LS3919 is the most suitable in order to replace LS3224, due to its satisfying relation geometric properties/weight. This modification can be also done with section type LS4302 or LS5252 if a lesser turret deformation is required.

6.6.4 Structural Part Strength Result

Stress on structural parts are given directly by FEM model and critical values are obtained according to the following table. These results are obtained with the completely defined solution. As can be seen, the critical structural part verified is E07-V/E08-V during Load Case 5.

Table 6-21 Stress, resume of FEM result for each Ultimate Condition Load Case

Load Case	Critical Structural Part	Max. VMES [MPa]	Tensile Yield Strength [MPa]	MS
1	E07-V/E08-V	149,1	503	2,374
2	E07-V/E08-V	173,91	503	1,892
3	E07-V/E08-V	165,9	503	2,032
4	E07-V/E08-V	164,59	503	2,056
5	E07-V/E08-V	197,54	503	1,546
6	E07-V/E08-V	163,8	503	2,071

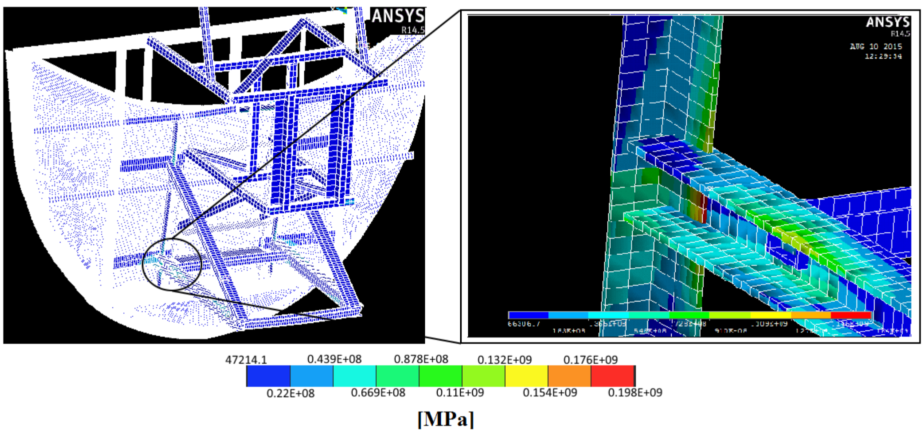


Fig. 6-26 Final solution critical tensile zone

6.6.5 Structural Part Deformation Result

Once again, deformation on structural parts are given directly by FEM model and critical values are obtained according to the following table.

Load Case	Max. Deformation in X [m]	Max. Deformation in Y [m]	Max. Deformation in Z [m]
1	1,06E-04	-0,002797	0,002396
2	2,20E-05	-0,003491	0,002628
3	-1,10E-04	-0,002798	0,002396
4	1,13E-04	-0,003635	0,002469
5	4,89E-05	-0,00443	0,002599
6	1,56E-05	-0,003771	0,002367

As verified, maximum deformation occurs during the limit conditions Load Case 5. Fig. 6-27 shows the general deformation of the turret platform and critical the deformation which is in yz orientation. In this referential, Load Case 5 deformation causes a 0,8° angle. These are the limit operation conditions faced by the turret. It is not possible to determine if this deformation will affect the turret's performance, thus, it is suggested to be taken in account during the contractual agreement with the EO/IR system manufacturer. Turret geometry observed on the Fig. below is purely schematic.

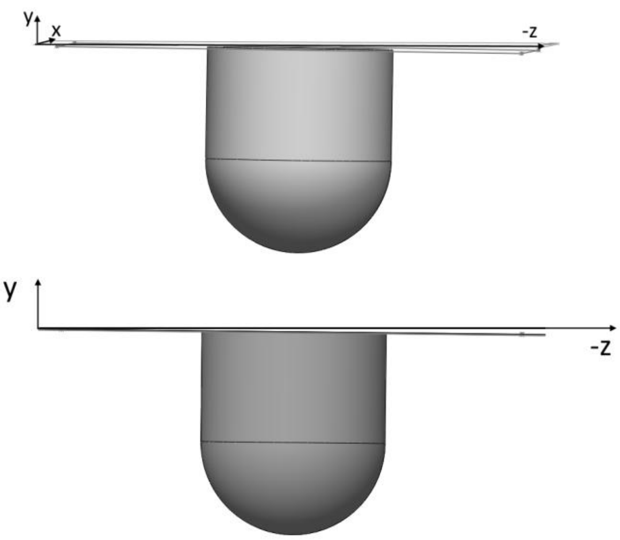


Fig. 6-27 Representation of the most critical deformation which is verified in yz

6.6.6 Other miscellaneous results

Performing a modal analysis of the turret structure, the natural frequencies were obtained, which are presented in Table 6-22.

Table 6-22 Modal analysis results

Mode	Natural Frequency [Hz]
1	21,5932
2	21,6695
3	21,7199
4	21,7984
5	23,4757
6	23,4898

6.7 Weight and Balance

6.7.1 Weight impact

For *LOCKHEED MARTING C-130 H*, Mean Aerodynamic Chord arm (MAC) is defined as 4,18 m (black rectangle on and Leading Edge Mean Aerodynamic Chord arm (LEMAC) is defined as 12,38 m.

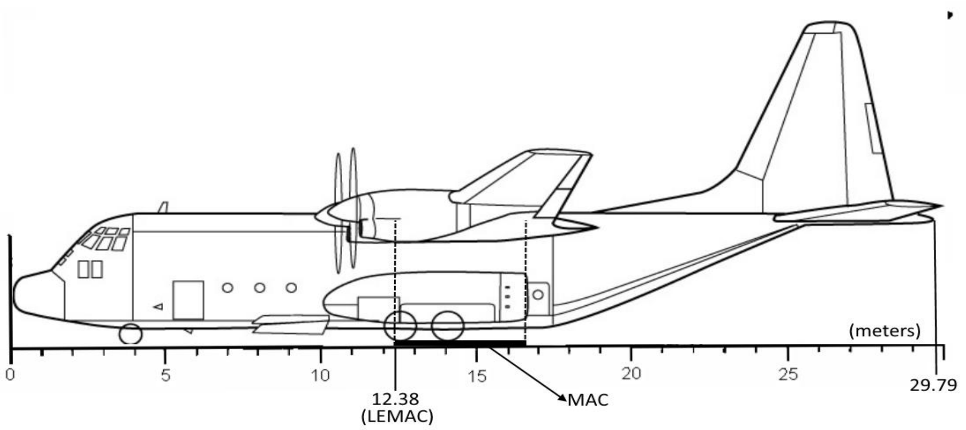


Fig. 6-28 Aircraft balance reference system

As stated in Chapter 5, the calculus of the new aircraft CG affected by turret installation can be described by:

$$CG_{\%MAC} = \frac{(CG_{DATUM} - 12{,}38)}{4{,}18} \times 100 \tag{6.1}$$

Standard Basic Empty Weight (BEW_{STD}) and Standard Basic Empty Moment are defined by *LOCKHEED MARTIN* C-130 Flight Manual[43].

Table 6-23 Aircaft CG modification due to tueer integration

$\mathbf{BEW_{STD}[kg]}$	31818,2
$\mathbf{BEM_{STD}\ [kg]}$	432409,3
$\mathbf{CG_{DATUM\ STD}\ [m]}$	13,59
$\mathbf{CG_{\%\ MAC.STD}\ [\%]}$	28,947

Following, are presented lists of removed and installed items during the modification and their respective impact.

6-24 List of removed item from aircraft modification

Type	**PART NO.**	**Weight [kg]**	**CG [m]**	**Moment [kg.m]**
Structural part	LS3224	0,75	2,362	1,773
	***Σ* weight removed**	**0.75**	***Σ* moment removed**	**1.773**

Table 6-25 List of installed items in aircraft modification

Type	**PART NO.**	**Weight [kg]**	**CG [m]**	**Moment [kg.m]**
Support Structure	SS-1_Mount	5,776	1,225	7,078
Electronic Equipment	FLIR STAR SAPHIRE III	44	1,975	86,887
	***Σ* weight removed**	**49,776**	***Σ*moment removed**	**87,965**

The modification result on additional weight, moment and new predicted CG are displayed below:

Table 6-26 Aircraft modification overall impact

Property	Value
Δ weight [kg]	49,026
$BEW_{modified}$ [kg]	31867,226
Δ moment [kg.m]	87,965
$BEM_{modified}$ [kg]	432497,303
$CG_{modified}$ [m]	13,572
$CG_{\%DATUM\ (modified)}$	0,285

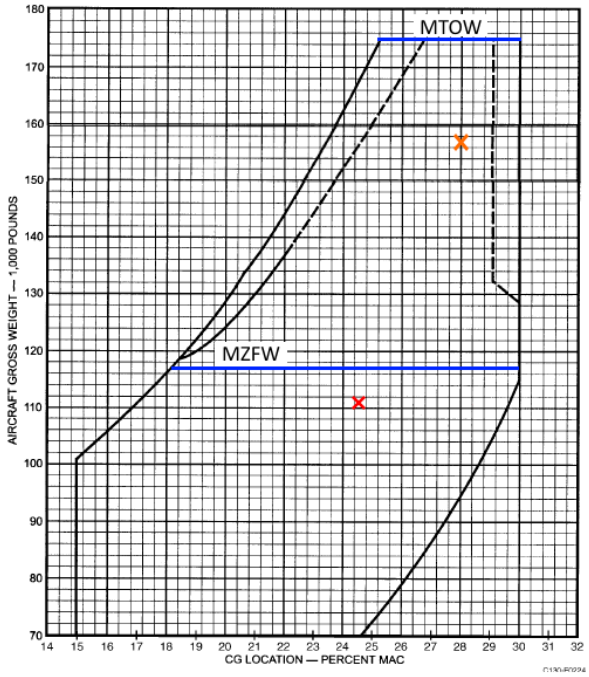
6.7.2 Balance verification

Verifying the diagram on Fig. 5-9, an estimate of OEW, ZFW and TOW is necessary in order to validate possible flight conditions. Table 6-27 contains the necessary information on which, maximum payload and maximum fuel weight were considered for conservative reasons. As can be verified, there is no predicted arm of operational weight because of inexistent information. However, it is considered that the impact would be negligible comparing to weight such as payload and fuel, which are 7 times greater.

Table 6-27 Impact of operational, payload and fuel weight on aircraft

	Weight [kg]	Arm [m]	Moment [kg.m]
Operational weight	2455,8	*	*
Max. Payload (2,5 G)	18955	13,132	248917,06
Max. Fuel Weight	20819	13,9	289384,1

Fig. 6-29 shows the CG limitations of this aircraft models, MTOW and MZFW limits and respective TOW and ZFW. It can be observed that the total weight resultant from this modification project is beneath the takeoff and landing limits Maximum Taxi Weight (MTW) could be identified for this aircraft model, hence, it will not be included in the Flight Envelope.



TAKEOFF AND LANDING LIMITS
INFLIGHT LIMITS (FLAPS AND GEAR UP)
× ZERO FUEL WEIGHT (ZFW)
× TAKEOFF WEIGHT (TOW)

	Weight [kg]	CG [m]	CG %MAC
OEW	34325,482	*	*
ZFW	50824,1	13,407	24,577
TOW	71643,682	13,550	27,999

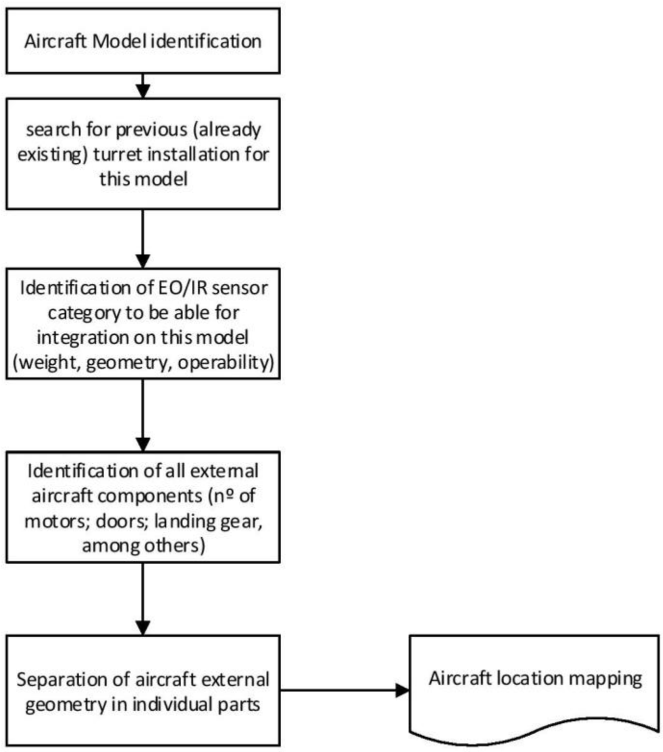
* ASSUMED VALUES FOR BEW AND BEM

Fig. 6-29 Center of gravity limitations

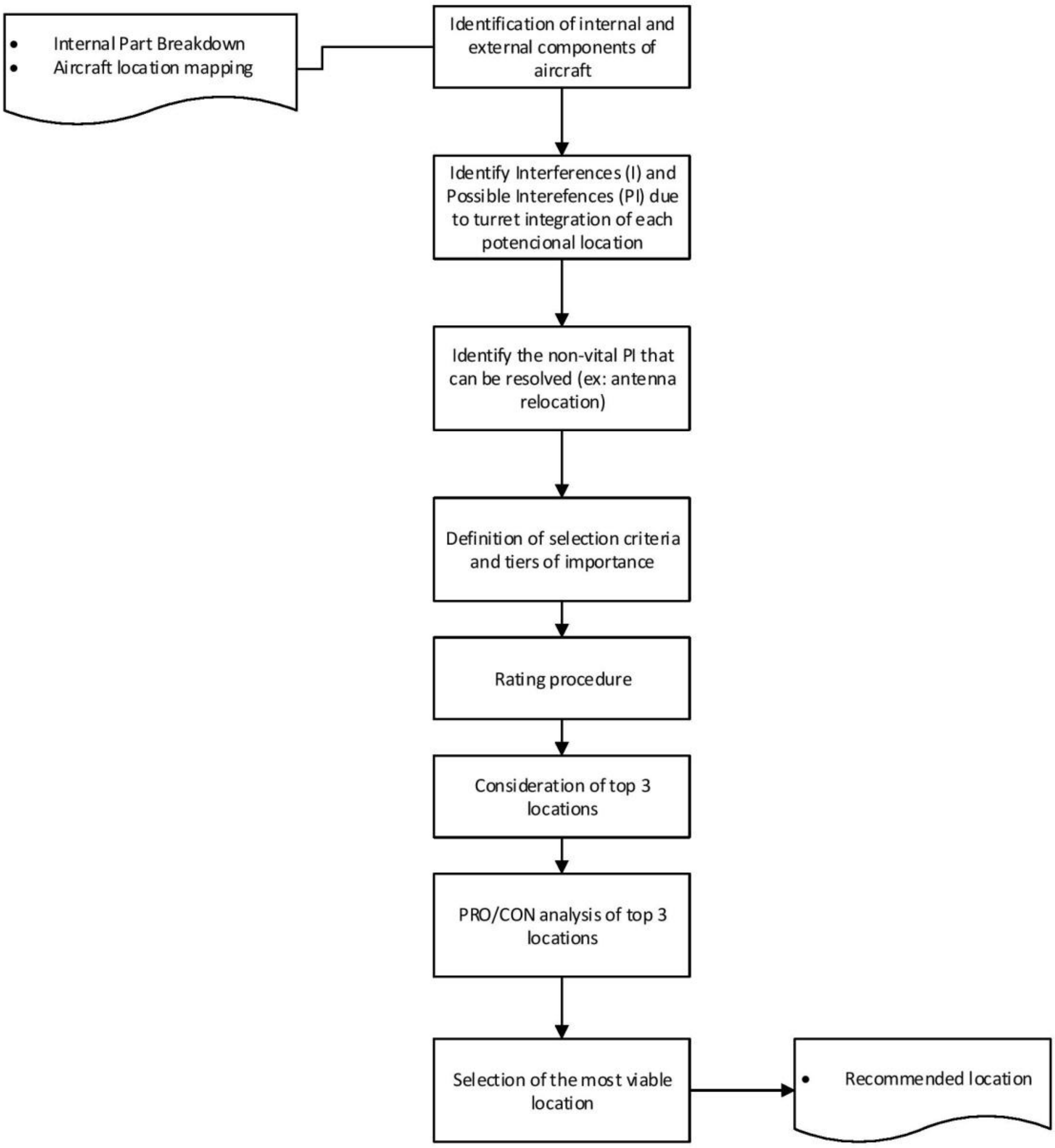
7 Methodology definition

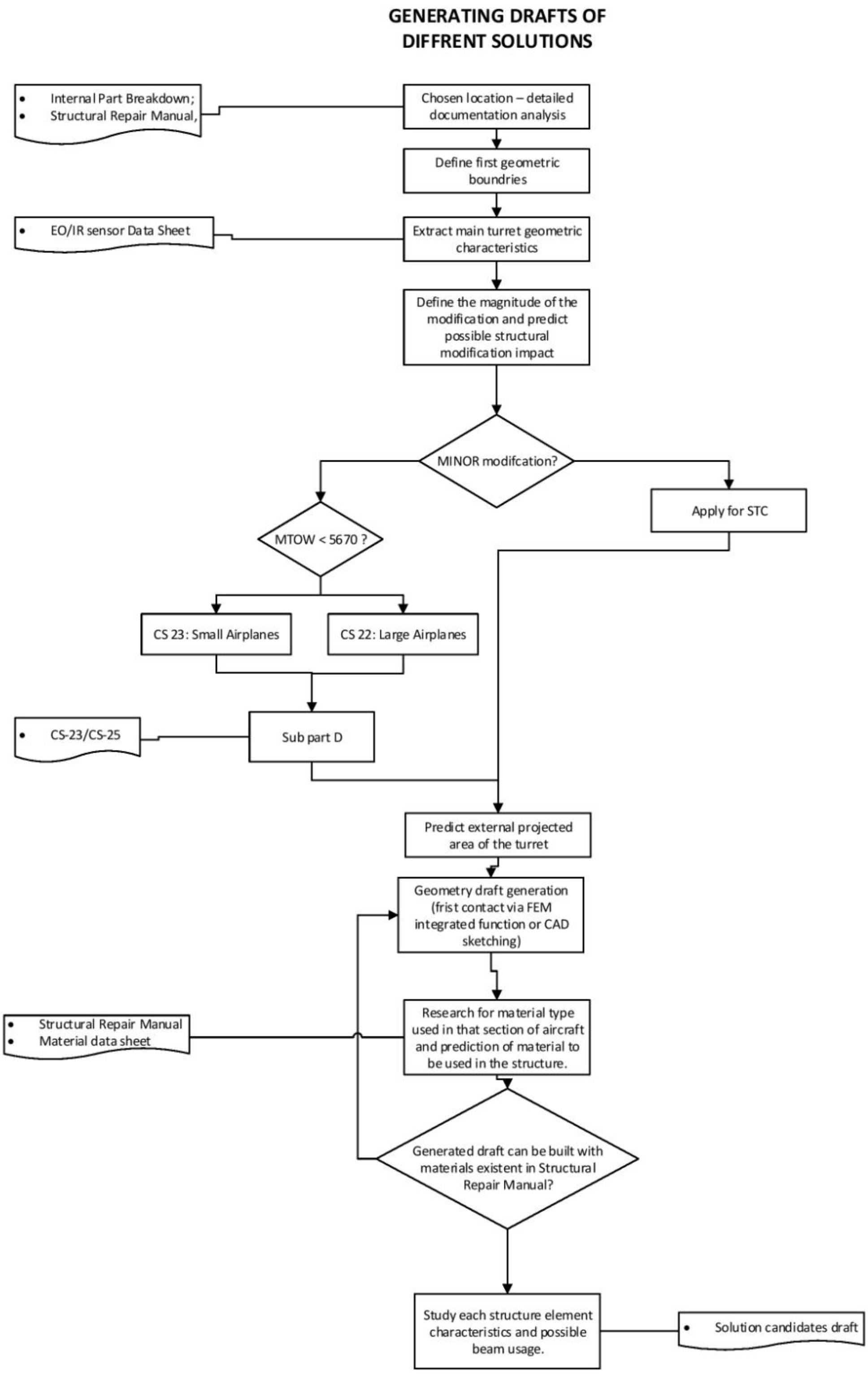
The final development chapter is intended to contain the definition of various procedures and steps to be followed during a similar project as one developed in this Case Study. Thus, this chapter is a more detailed approximation of Preliminary Analysis, stated in Fig. 3-5. these procedures are presented as fluxograms in this chapter.

LISTING OF POSSIBLE SENSOR LOCATIONS SUBJECT TO FURTHER MODIFICATIONS

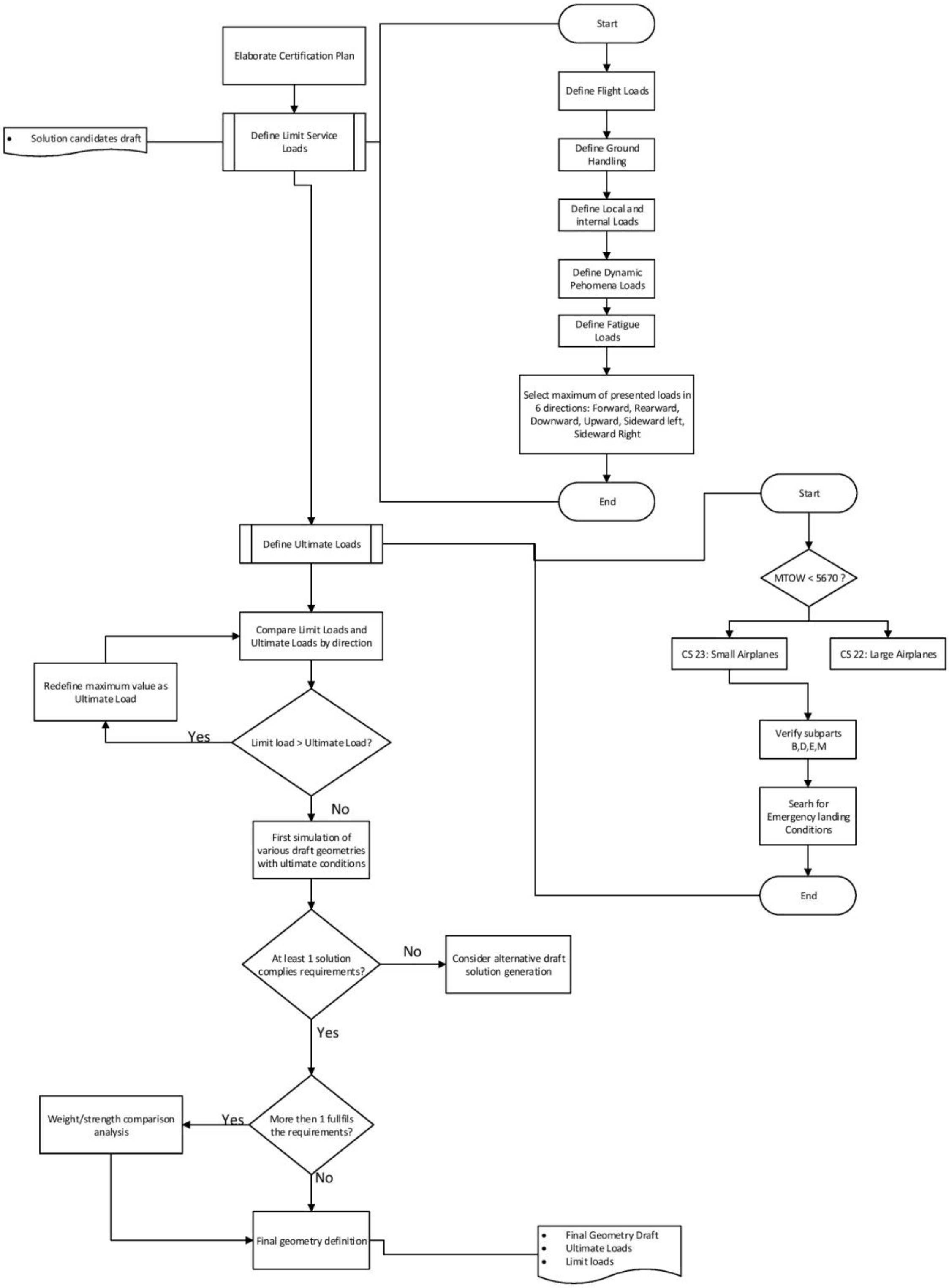


LOCATION ANALYSIS AND MAPPING OF THE VIABILITY OF EACH ONE

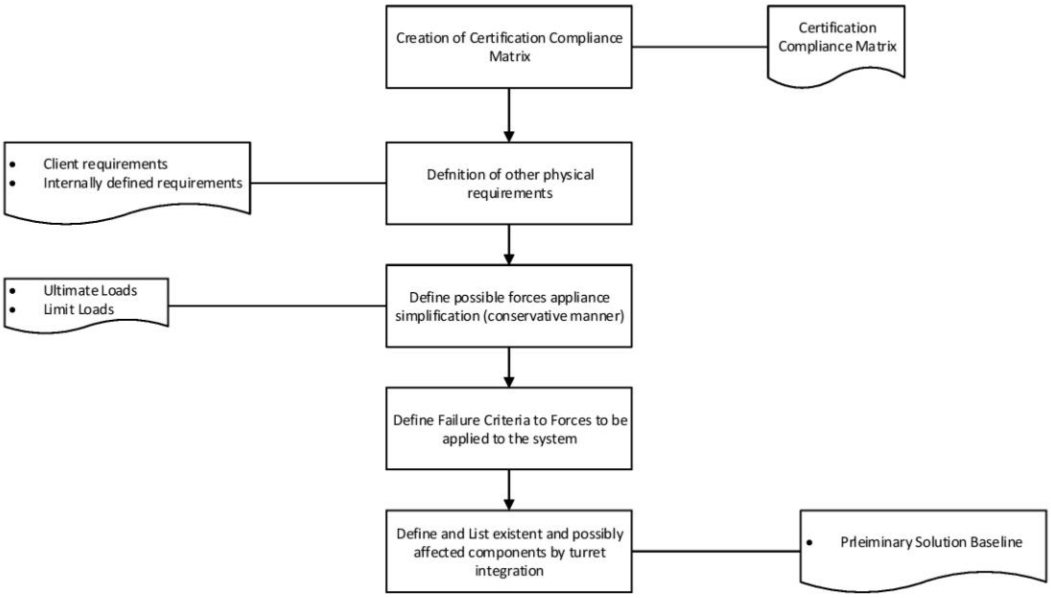



GENERATING DRAFTS OF
DIFFRENT SOLUTIONS
Internal Part Breakdown;
Structural Repair Manual,
Chosen location – detailed documentation analysis
Define first geometric boundries
EO/IR sensor Data Sheet
Extract main turret geometric characteristics
Define the magnitude of the modification and predict possible structural modification impact
MINOR modifcation?
Apply for STC
MTOW < 5670 ?
CS 23: Small Airplanes
CS 22: Large Airplanes
CS-23/CS-25
Sub part D
Predict external projected area of the turret
Geometry draft generation (frist contact via FEM integrated function or CAD sketching)
Structural Repair Manual
Material data sheet
Research for material type used in that section of aircraft and prediction of material to be used in the structure.
Generated draft can be built with materials existent in Structural Repair Manual?
Study each structure element characteristics and possible beam usage.
Solution candidates draft

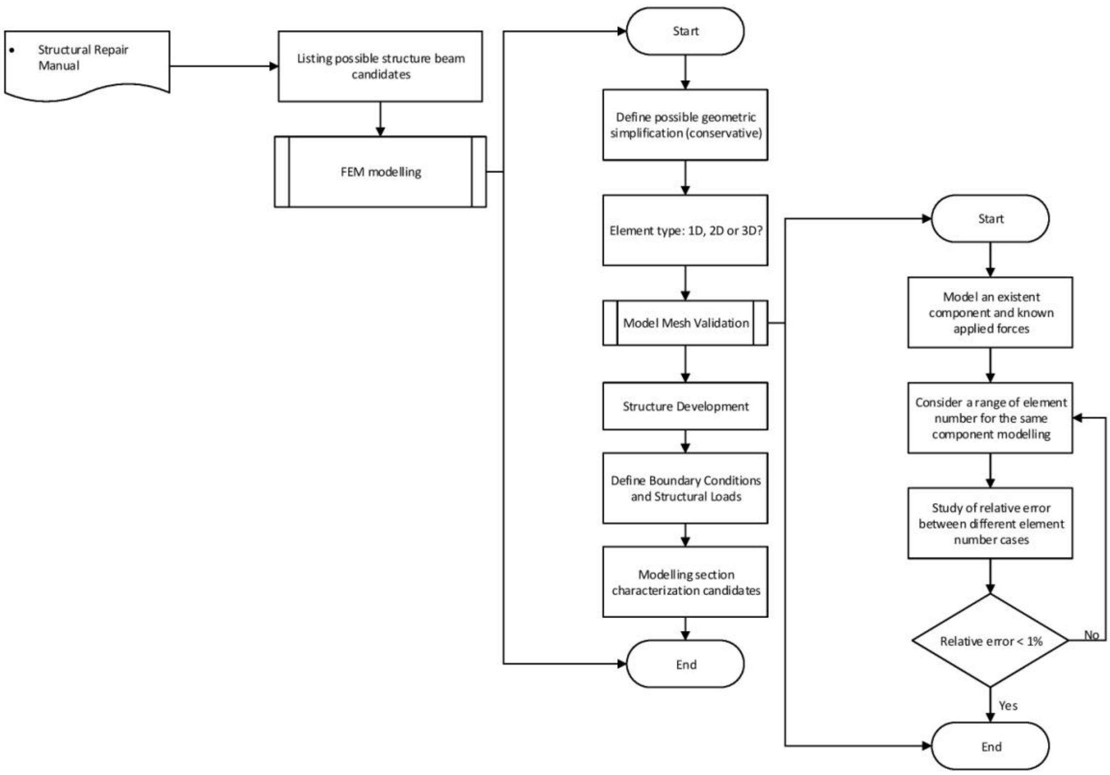
SELECTION OF THE MOST TECHNICALLY VIABLE SOLUTION



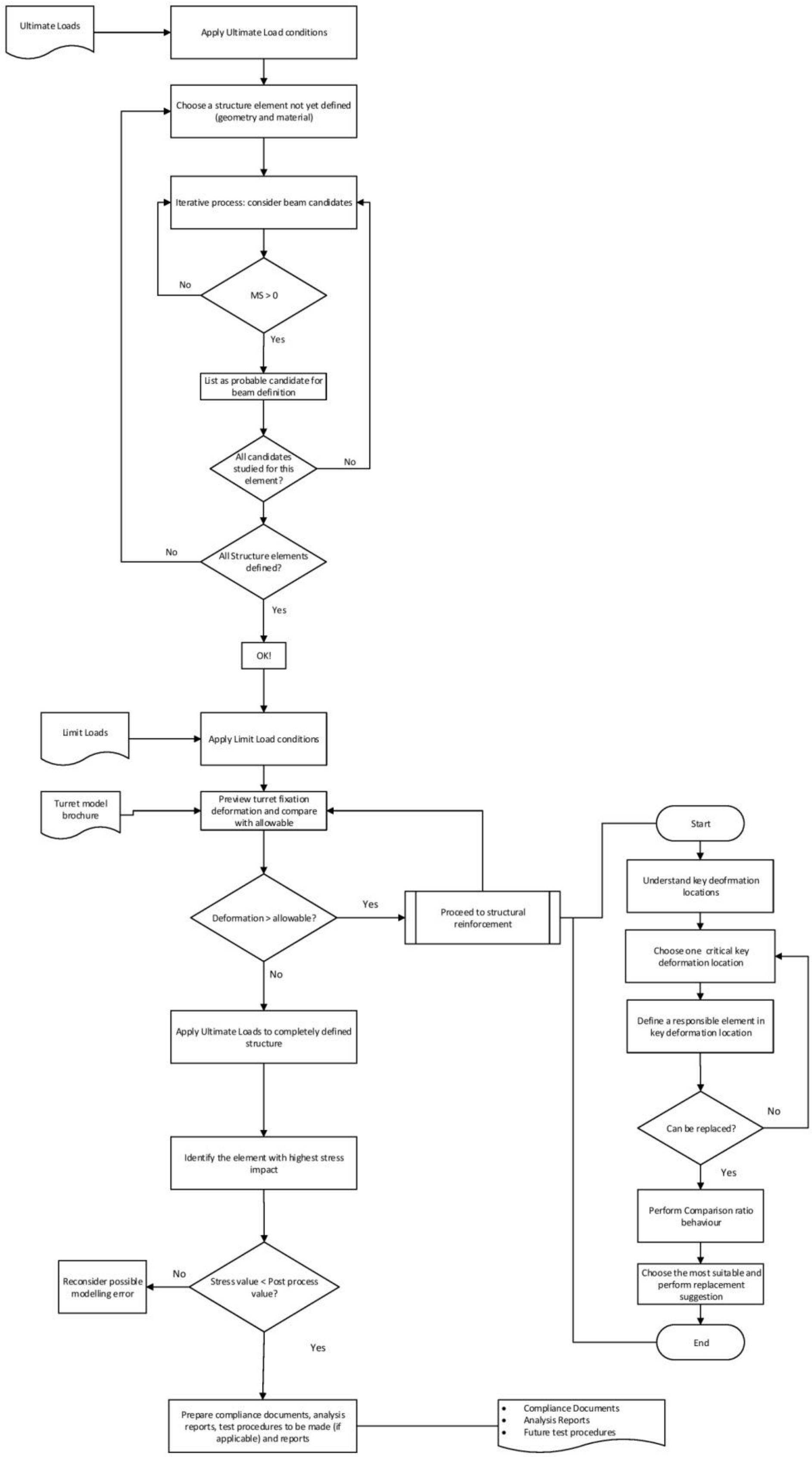
DEVELOPMENT STEPS AND PHYSICAL REQUIREMENTS

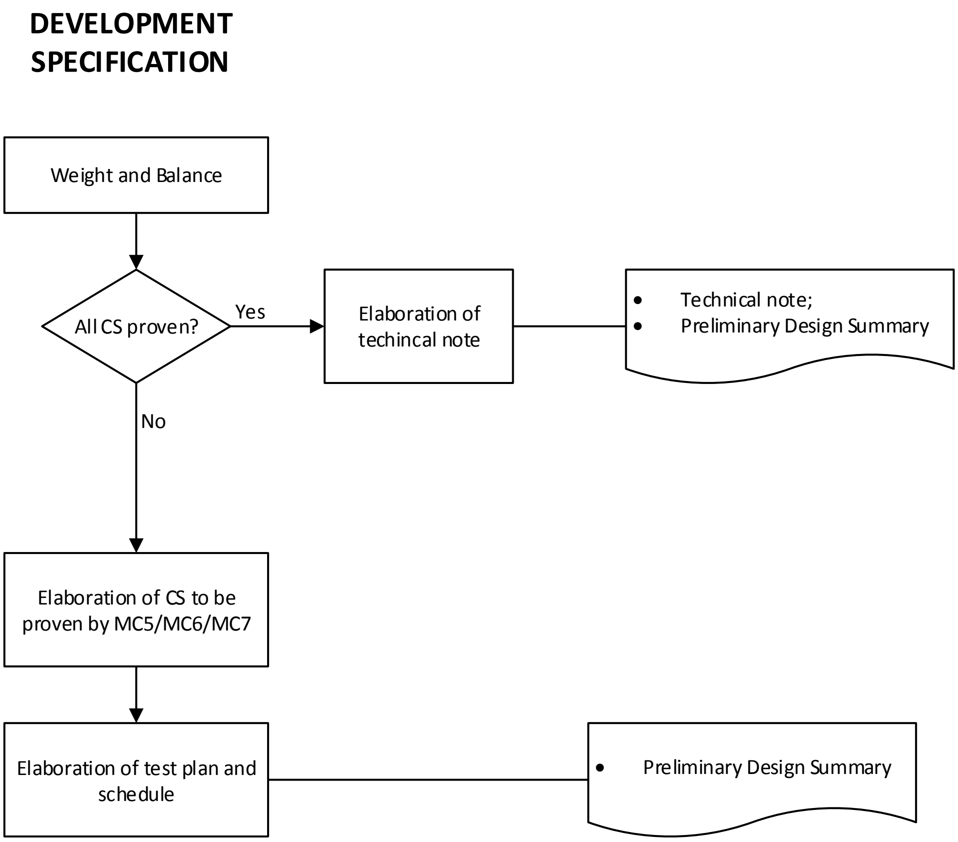


PRELIMINARY SOLUTION DEVELOMENT



ANALYTIC AND NUMERICAL SIMULATIONS





The developed diagrams describe the proposed methodology for the aircraft modification procedure and can be viewed as one of the main contribution from this dissertation.

8 Conclusion

8.1 Concluding remarks

This work is performed in order to be a guidance for future possible projects of EO/IR sensor turret installation on a military type aircraft. During the systematic approach to the typical modification project, it was possible to develop a valuable procedure tool that could deliver a quick, effective and valuable response for a project of this nature.

The analysis of the Case Study is, in fact, the most time taking procedure of the project. Nerveless, this was a necessary procedure in order to overcome in more detail the possible obstacles to occur. As can be seen from Fig. 6-18 to Fig. 6-22, identification of critical sections during the critical Load Case appliances is showed. Identification of critical element areas is considered important for future analysis of this structure. Considering that most of the critical area are joints of various elements, no additional element drilling is recommended for electronic equipment installation or electric cable system passage. These areas are the most expected to suffer from a fatigue stress cycle, and so, during any maintenance or inspection procedure, special focus on these areas is required.

Modification of the bulkhead original structure (substitution of LS3224 by LS3919) has a direct impact on the turret support structure. As can be seen in Table 6-21, the critical stress is verified in element E07-V/E08-V. However, its worst case scenario (Load Case 5) registers a considerably lower stress than the one considered during the structure element definition. Thus, it is concluded that the structure can appear as slightly over dimensioned. Stating the fact that the modelling of elements left out eventual "holes" for elements connectors (rivets or fasteners), which present stress concentration factors in critical areas. Thus, this is a cause of incensement of the maximum stress value. In overall this over dimensioning result can be taken into account as a positive approximation.

Post-process analysis of other miscellaneous results as support structure natural frequencies, it is suggested that the Dynamic Amplification Factor (DAF) is kept $\gg 1$. Knowing that $\omega_n = \text{natural frequency}, \omega_f = \text{forced frequency and that } r(DAF) = \frac{\omega_n}{\omega_f}$, the approximation of this ratio to 1 could be extremely harmful to the system, considering that there is no damping. Further investigation and more detailed analysis to this subject should be done in the future.

The approximation of Weight and Balance study verified that in fact, the conducted modification project is contained in the limits of the given model aircraft flight envelope (Fig. 6-29). As stated, the total support structure weight is 5,8 kg, which is only 11% of total modification project weight.

8.2 Main concerns and future considerations

Taking in consideration future works, following topics should be explored: Connection between various elements - as was specified, the type of union between different element predicted during the project was in fact through rivets or fasteners. This element joint type should be explored and projected in order to complete the structure support project.

Fatigue analysis - As verified, during this study a static and modal analysis was made. However, fatigue analysis should be done in order to verify the amount of possible fatigue cycles. Along with the procedure of fatigue analysis, bulkhead pressurized area (that was not considered for this project) should be considered. For the structure life estimation, Palmgren-Miner method of analysis should be employed. This fatigue damage theory states that the fatigue damage incurred at a given stress should be evaluated by the ratio of number of cycles applied at that stress level divided by the total number of cycles to cause failure at that same level [39]. When the ration reaches 1, the material fails. This study should be based on empirical result about material behaviour charts.

$\boldsymbol{k}$ = *Number of stress levels considered in the analysis* $\boldsymbol{n_i}$ = *Number of loading cycles′ at* i^{th} *stress level* $\boldsymbol{N_i}$ = *Number of loading cycles to failure at* i^{th} *stress level*	$D = \sum_{i=l}^{k} (\frac{n_i}{N_i})$	(8.1)

Some of the main concerns about the turret installation is the possible damage during aircraft towing. It is unclear what is the normal procedure during a towing procedure, however a technical minute should be prepared in order to predict any modification during that particular procedure.

During this work, time factor was one of the major concerns to be accounted during the project definition. Consecutive conservative measures resulted in a structure that withstand the requirements with a satisfactory MS. For future considerations, the decreasing of this MS can be studied and thus, a geometry optimization can be conducted, however in a discrete set of elements.

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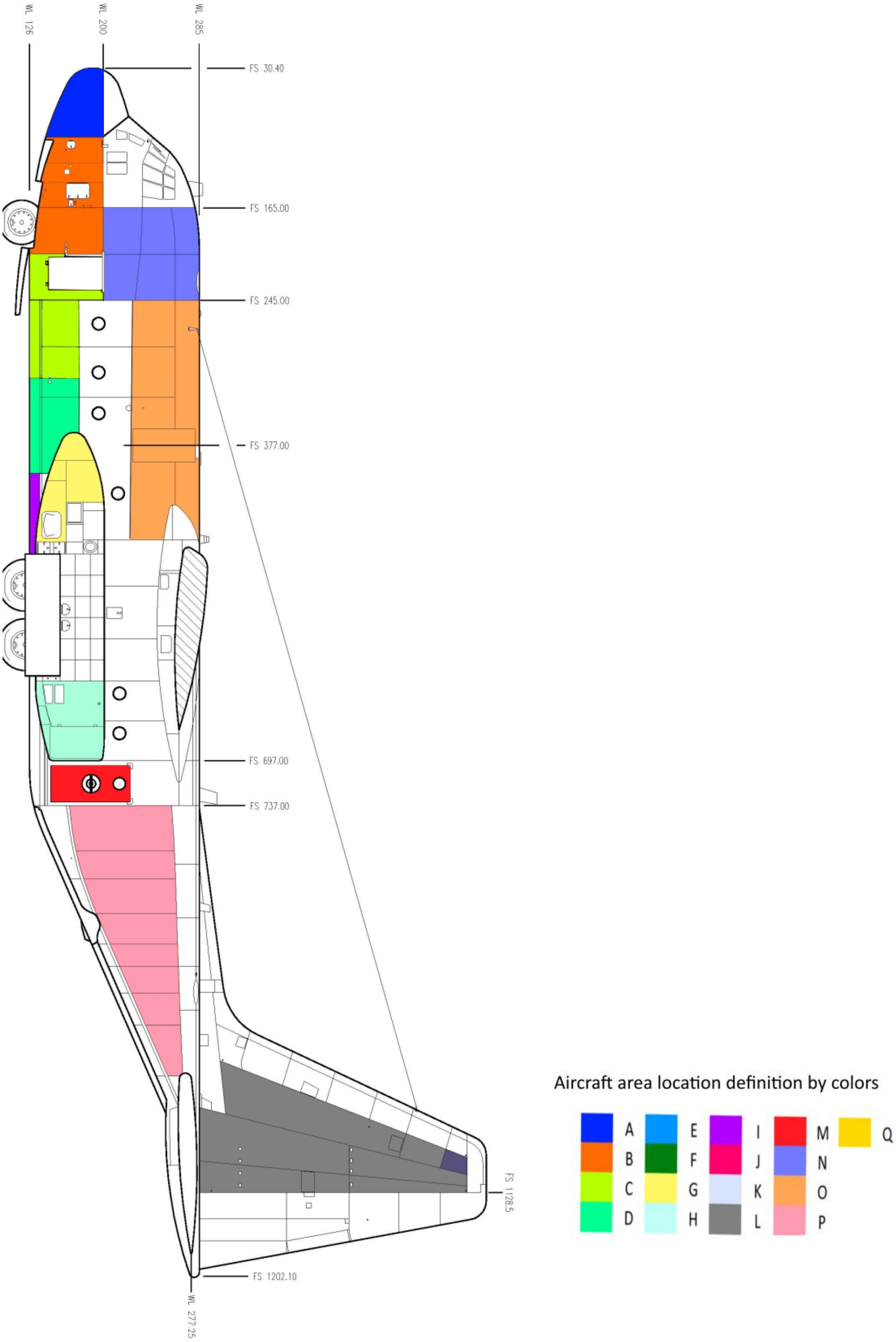
APPENDIX A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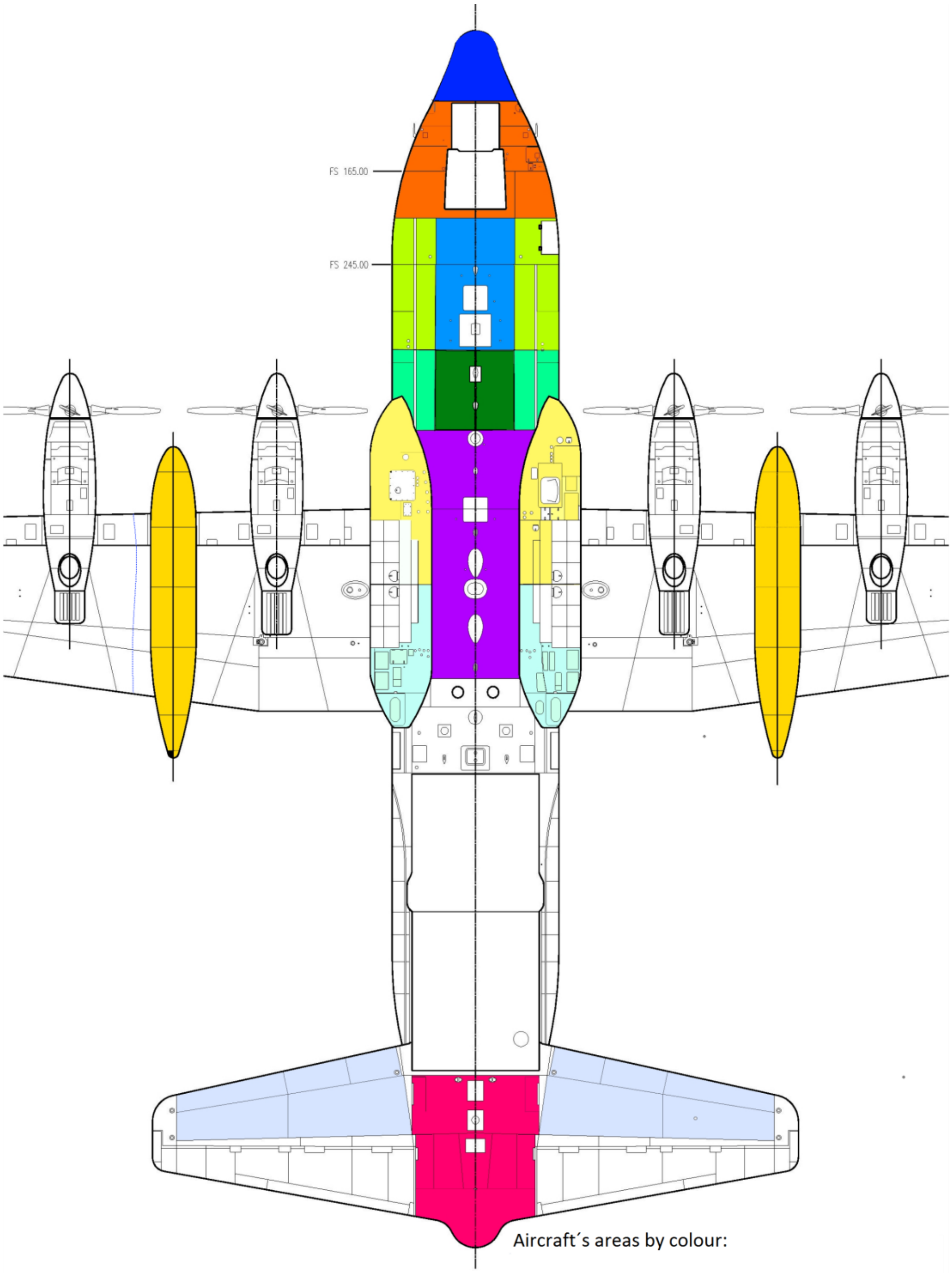
WL 200
WL 285
FS 30.40
FS 165.00
FS 245.00
FS 377.00
FS 697.00
FS 737.00
FS 1128.5
FS 1202.10
WL 277.25
Aircraft area location definition by colors
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q



Aircraft´s areas by colour:

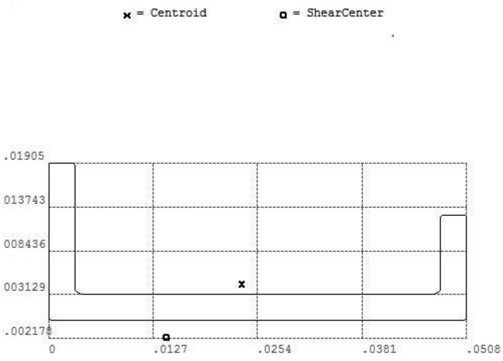
A	E	I	M	Q
B	F	J	N	
C	G	K	O	
D	H	L	P	

APPENDIX B

Criteria		Location	Decision/Justification
1		L	As it is on the side, it would need sensors in both sides and the K area is blocking the sensors' sight
		M	Not under the fuselage enough
		N, O	Mounting the turret on the upper side of the fuselage station does not allow any range of sight
		P	To have an adequate sight range it would need a sensor in both sides and it would have to be in the lowest part of the area P
		Q	The only way is to attach a supporting structure to the fuel tank with the sensor facing down
2	2.1	A	Antenna 20 must be relocated if an interference is detected
		E	The distance between the sensor to antennas 17,18 e 19 must be checked
		F	The distance between the sensor to antennas 17,5 e 6 must be checked
		N	The distance between the sensor to antenna 3 must be checked
	2.2	A, B	nose landing gear
		C,D,F,G,E,I	main landing gear
		E, I	some antennas
		K	elevators
		L	rudder
		M	door M
		P	elevators
		Q	flaps and ailerons
	2.3	K	elevators
		L	rudder
		Q	wing and flaps
	2.4	B	interphone and liquid oxygen drain/vent - must mind these components when designing the fixation
		C,D,F	These locations meet the FAP C-130H but there are usual modifications in these locations that one might have to consider
		E	Interference with the nose landing gear sliding cover
		G,H	Possible interference with the main landing gear cover
		M	Door M
	2.5	A	PI - Landing Gear Hydraulic Pumping (IPB - Hydraulic Systems p.111). Bleed Air Anti-Icing system (IPB - Pneumatic System p.61). Pitot Static Systems (IPB - Pneumatic System p.231)
		B	PI - on the right: external interphone(TMC p.17).on the left: booster hydraulic system ground test connection acess, Liquid Oxygen Valve/Vent(TMC p.141). Hydraulic Brake Piping (IPB - Hyrdaulic Systems p.75). Metering Valve (IPB - Hyrdaulic Systems p.91). Electrical Components (IPB - Electrical Systems p. 171). Battery Equipment (IPB - Electrical Systems p. 181)
		C	PI - fuselage drainage holes(TMC p.141) Hydraulic Brake Piping (IPB - Hyrdaulic Systems p.75). (à direita) Flight Deck Air Conditioning System (IPB - Pneumatic System p. 83). Electrical Components (IPB - Electrical Systems p. 171). Battery Equipment (IPB - Electrical Systems p. 181). AFT Center Equipment (IPB - Eletronic System p.51)
		D,E,F	PI - fuselage drainage holes (TMC p.141)
		G	I - (on the right) Refrigeration Unit . PI - (on the left): Cargo compartment refrigerator acess(TMC p.18). Water separation drain(TMC p.141). Air intake Drain(TMC p.141). Hydraulic Vent(TMC p.141). Landing Gear Failing Drainage Holes(TMC p.141). PI - (à direita) APU air intake door (TMC p.331). Hydraulic Brake Piping (IPB - Hyrdaulic Systems p.97). APU Bleed Air Supply system (IPB - Pneumatic Systems p.161)
		H	PI - single point refuel drain valve/adapter drain. Fuel Pump seal drain. Hydraulic Brake Piping (IPB - Hyrdaulic Systems p.97)
		I	PI - fuselage drainage holes
		J	I - elevator trib tab motor acess, Controls inspection acess, Pressure seals and structural inspection, Rudder and elevator controls and electrical acess, Rudder and elevator . controls and electrical acess, AFT empennage draining holes. PI - Elevator and Rudder Controls (TMC p.287)
		K,L	I - anti-icing
		N,O	PI - IFF (IPB - Electronic System p. 87)
		P	PI - Auxiliary Hydraulic Piping (IPB - Hydraulic Systems p.171). Caution with AFT Fuselage Electronic (IPB - Electronic System p.109)
		Q	PI - Fuel Tank
3		C,D	Susceptible to dust and rocks from the nose landing gear
		E,F	Dangerously close and behind the nose landing gear
		G,H,I	Close to the ground
		J,K	High temperatures may affect the sensor and the exhaust gas may affect the sensor's lenses
		P	In the location that enables a full range of sight, the sensor may be too close and behind the main landing gear

4	C,D,E,F,I,M,N,O,P	Pressurized area of the aircraft
5A	A,B,C,D,E,F,G,H,I	A bigger sensor may affect the aircraft's aerodynamics. The location is in the fuselage where the air flow is well difinied
	J	May affect the CD
	K,L	Bigger size is critical to the good functioning of the elevators and rudder
	M,N,O	The aerodynamics must be checked if considering a bigger sensor
	P	The only way to reduce the impact is to create an aerodynamic external structure to support the sensor
	Q	The wing balance affects the flight performance of the aircraft. NEEDS Sensors on BOTH wings
5B	A	Relatively simple fixation needing only structural reinforcements
	B,C,D,N,O,P	Needs small external structure to support the sensor turret
	G,H	Needs bigger external structure to support the sensor turret
	J	Sensitive aircraft location (Structural and Operationalwise)
	K,L	Sensitive and small areas, not viable
	M	It is an attachment to the door, it is limited
	Q	Structurally, does not affect significantly the wing
6	A	Bulkhead partial removal is required. A hole drilling procedure
	B,C,D,E,F,I,N,O,P,Q	Frames
	G,H	Near the frames
	K,L	Sensitive aircraft location
	M	There is the need to guaratee the resistence of the door
	J	Area required to detailed analysis
7	A	Hole + Fixation (relatively simple)
	B,C,D	Requires an external structure
	E	Landing gear sliding door and many antennas (interference)
	F,I	Hole + Fixation (Mind the distance between antennas!)
	G,H	Involves a big external structure to support the sensor
	J	Numerous intereferences (operational, strucutral, geometrical) that may not allow the fixation
	K,L	Sensitive areas and critical operational functions
	M	Concern about the link between the door and the sensor, as well as the type of fixation. It no longer is as a door.
	N,O	To provide a good sight range, there would be necessary a huge arm to the sensor
	P	Might need sensors on both sides or a big external structure
	Q	Difficulties in attaching the structure of the sensor to the fuel tank

APPENDIX C



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Torsion Constant
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Centroid Z
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Shear Center Y
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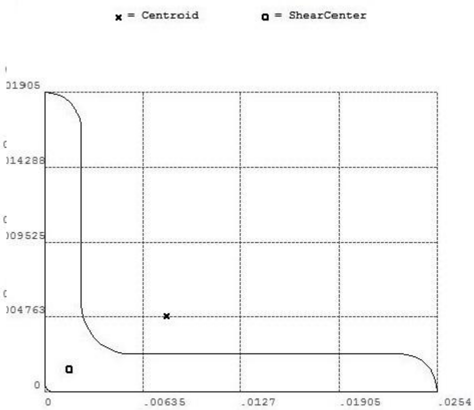

LS1463

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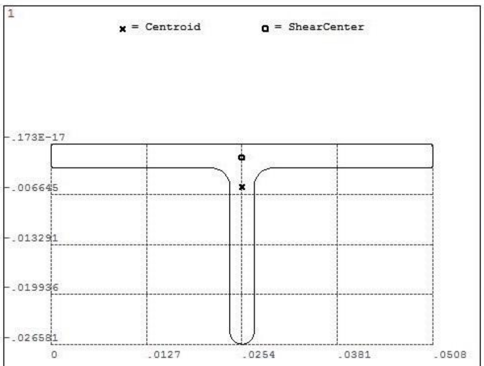

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Shear Corr. YZ
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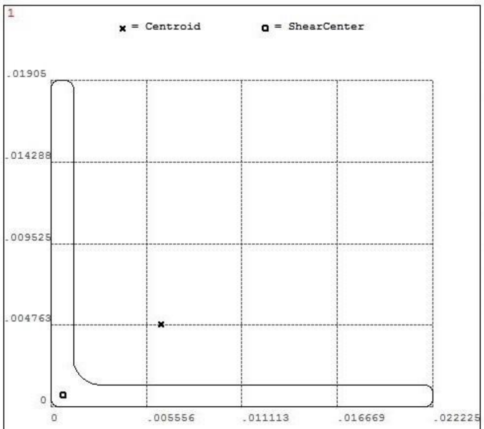
Shear Corr. ZZ



LS2469

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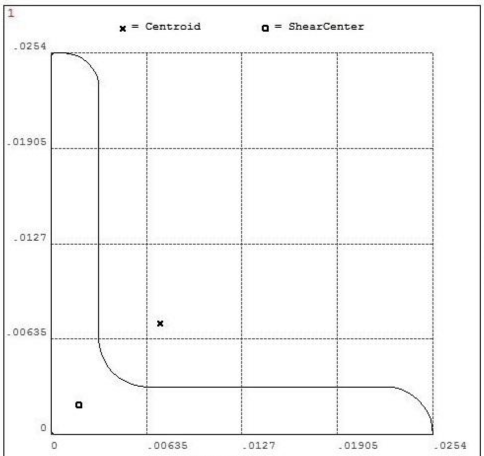

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Shear Center Y
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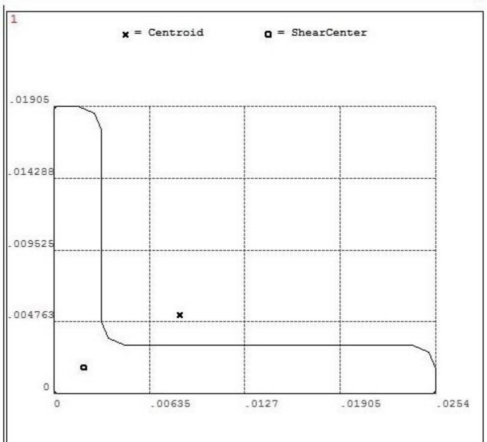

LS3254-3

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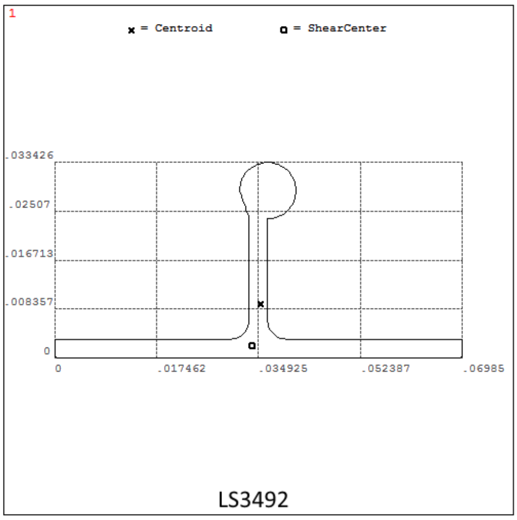
Torsion Constant
= .445E-09
Centroid Y
= .008358
Centroid Z
= .005196
Shear Center Y
= .00202
Shear Center Z
= .001681
Shear Corr. YY
= .52915
Shear Corr. YZ
= -.01215
Shear Corr. ZZ

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Iyz
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Izz
   = .906E-07
Warping Consta
   = .400E-12
Torsion Consta
   = .200E-08
Centroid Y
   = .035242
Centroid Z
   = .009193
Shear Center Y
   = .03381
Shear Center Z
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Shear Corr. YY
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Shear Corr. YZ
   = .012111
Shear Corr. ZZ
   = .228009
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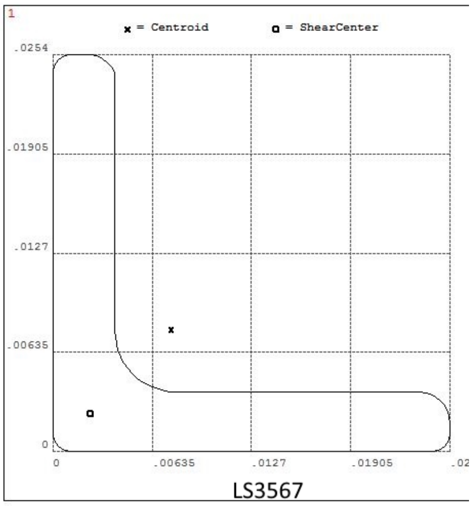

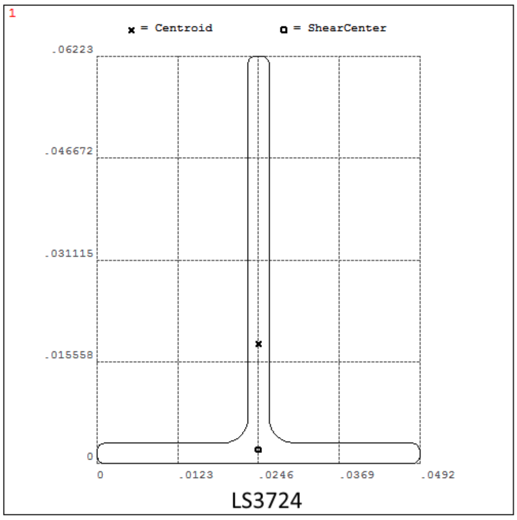


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SECTION ID 2
DATA SUMMARY

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Iyy
   = .137E-06
Iyz
   = -.126E-10
Izz
   = .310E-07
Warping Constant
   = .216E-12
Torsion Constant
   = .132E-08
Centroid Y
   = .024602
Centroid Z
   = .018277
Shear Center Y
   = .024605
Shear Center Z
   = .00209
Shear Corr. YY
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Shear Corr. YZ
   = -.539E-03
Shear Corr. ZZ
   = .474024
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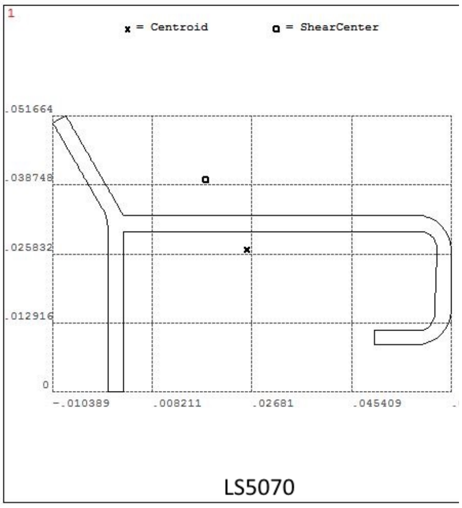

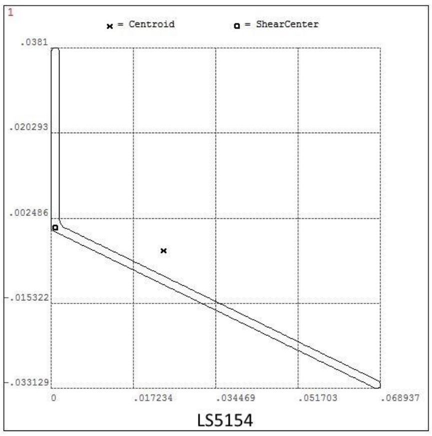


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SECTION ID 1
DATA SUMMARY

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Iyy
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Iyz
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Izz
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Warping Constant
   = .598E-13
Torsion Constant
   = .170E-09
Centroid Y
   = .023476
Centroid Z
   = -.004345
Shear Center Y
   = .928E-03
Shear Center Z
   = .450E-03
Shear Corr. YY
   = .471384
Shear Corr. YZ
   = -.240102
Shear Corr. ZZ
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APPENDIX D

E01-H/E02-H

Table 9-1 Geometric considerations and Buckling Tension of Channel sections for E01-H/E02-H

PART NO.	A (m)	Iyy (m^4)	Izz (m^4)	Buckling Force (N)	Buckling Ten-sion (Pa)
LS264	1,15E-04	2,56E-08	4,02E-09	6,86E+03	5,963438E+07
LS328	1,51E-04	1,71E-08	6,35E-09	1,08E+04	7,195070E+07
LS2024	2,67E-04	4,33E-08	5,27E-08	9,01E+04	3,378771E+08
LS2367	2,11E-05	4,81E-08	1,05E-08	1,76E+04	8,347527E+08
LS2430-3	6,01E-04	1,89E-07	8,10E-08	1,36E+05	2,257430E+08
LS2726-3	2,10E-04	8,29E-08	1,30E-08	2,18E+04	1,037745E+08
LS3238	9,47E-05	4,82E-09	1,41E-09	2,41E+03	2,544260E+07
LS3360	3,63E-04	2,15E-07	2,71E-08	4,63E+04	1,276687E+08
LS3360-2	3,63E-04	2,15E-07	2,71E-08	4,54E+04	1,252236E+08
LS3471-2	3,02E-04	1,15E-07	1,81E-08	3,03E+04	1,001612E+08
LS4345	2,65E-04	7,13E-08	1,64E-08	2,75E+04	1,039979E+08
LS4386	1,15E-04	3,71E-08	2,22E-09	3,79E+03	3,282586E+07
LS4436	2,68E-04	4,73E-08	2,19E-08	3,73E+04	1,393631E+08
LS5001	6,87E-04	7,02E-07	6,62E-08	1,11E+05	1,613408E+08
LS5120	2,12E-04	2,58E-08	1,01E-08	1,70E+04	8,019692E+07

Table 9-2 Geometric considerations and maximum Crippling stress

PART NO.	Width (in.) [b]	Thickess (in.) [t]	b/t	Crippling Stress (ksi)	Crippling Stress (Pa)
LS264	0,0381	0,062	24,19354839	37,5	258553398,5
LS328	0,028575	0,062	18,14516129	38	262000777,1
LS2024	0,030175	0,093	12,77410888	38	262000777,1
LS2367	0,0381	0,13	11,53846154	69,5	479185631,9
LS2430-3	0,04868	0,188	10,19433741	69,5	479185631,9
LS2726-3	0,0507746	0,085	23,51764706	53,5	368869515,2
LS3238	0,01905	0,094	7,978723404	38	262000777,1
LS3360	0,0635	0,125	20	38	262000777,1
LS3360-2	0,0635	0,125	20	60	413685437,6
LS3471-2	0,0508	0,125	16	69,5	479185631,9
LS4345	0,042164	0,12	13,83333333	69,5	479185631,9
LS4386	0,04826	0,06	31,66666667	30	206842718,8
LS4436	0,033528	0,125	10,56	38	262000777,1
LS5001	0,08255	0,25	13	69,5	479185631,9
LS5120	0,028575	0,125	9	69,5	479185631,9

Table 9-3 Load Case 1 - E01-H/E02-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	1020,5	324	-0,682508574	-0,94156357	-0,746640472
LS328	1031,5	324	-0,685894329	-0,930246536	-0,746000216
LS2024	1310	324	-0,752671756	-0,742078512	-0,799999407
LS2367	748,65	503	-0,328123956	0,115010648	-0,359933705
LS2430-3	203,7	503	1,469317624	0,108213211	1,3524086
LS2726-3	725,03	503	-0,306235604	-0,856868625	-0,491235514
LS3238	2671,1	324	-0,878701658	-0,990474862	-0,901912779
LS3360	393,55	324	-0,176724686	-0,675597196	-0,334263049
LS3360-2	389,58	503	0,291134042	-0,678567607	0,061875449
LS3471-2	522,22	503	-0,036804412	-0,808201168	-0,082406587
LS4345	595,77	503	-0,155714454	-0,825439547	-0,195686873
LS4386	2012,3	324	-0,83899021	-0,983687392	-0,897210794
LS4436	567,96	324	-0,429537291	-0,754625186	-0,53869854
LS5001	165,63	503	2,036889452	-0,025896283	1,893108929
LS5120	881,07	503	-0,429103249	-0,908977806	-0,456132167

Table 9-4 Load Case 2 - E01-H/E02-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	1578,6	324	-0,794754846	-0,96222325	-0,836213481
LS328	1297,2	324	-0,750231267	-0,944533844	-0,79802592
LS2024	430,41	324	-0,247229386	-0,214987688	-0,391276278
LS2367	778,76	503	-0,354101392	0,071899843	-0,384681247
LS2430-3	203,29	503	1,474297801	0,110448281	1,357152993
LS2726-3	723,25	503	-0,304528171	-0,856516363	-0,489983387
LS3238	2035,5	324	-0,84082535	-0,987500567	-0,871284315
LS3360	388,63	324	-0,166302138	-0,671490304	-0,325834915
LS3360-2	388,43	503	0,29495662	-0,677615963	0,065019277
LS3471-2	520,77	503	-0,034122549	-0,807667135	-0,079851697
LS4345	594,29	503	-0,153611873	-0,825004827	-0,193683838
LS4386	2001,7	324	-0,838137583	-0,983601009	-0,896666474
LS4436	557,59	324	-0,418927886	-0,750061731	-0,530119304
LS5001	164,91	503	2,050148566	-0,021643329	1,905740294
LS5120	878,85	503	-0,427661148	-0,908747881	-0,454758341

Table 9-5 Load Case 3 - E01-H/E02-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	1340,9	324	-0,758371243	-0,955526604	-0,807179209
LS328	1300,7	324	-0,75090336	-0,944683096	-0,798569403
LS2024	429,67	324	-0,245932925	-0,213635699	-0,390227902
LS2367	776,28	503	-0,352037924	0,075324267	-0,382715474
LS2430-3	203,51	503	1,471623016	0,109247856	1,354604844
LS2726-3	720,67	503	-0,302038381	-0,856002691	-0,488157527
LS3238	2968,1	324	-0,890839257	-0,991427986	-0,91172778
LS3360	386,83	324	-0,16242277	-0,66996168	-0,322697885
LS3360-2	386,62	503	0,301019089	-0,67610669	0,07000527
LS3471-2	518,56	503	-0,030006171	-0,806847451	-0,075930207
LS4345	592,12	503	-0,150510032	-0,824363505	-0,190728852
LS4386	2003,7	324	-0,838299147	-0,983617378	-0,896769617
LS4436	555,98	324	-0,417245225	-0,749337963	-0,52875863
LS5001	163,94	503	2,068195681	-0,01585459	1,922932975
LS5120	828,4	503	-0,392805408	-0,903190579	-0,421552835

Table 9-6 Load Case 4 - E01-H/E02-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	1496,5	324	-0,783494821	-0,960150767	-0,827227933
LS328	1295,8	324	-0,749961414	-0,944473918	-0,797807704
LS2024	431,01	324	-0,248277302	-0,216080487	-0,39212367
LS2367	780,72	503	-0,355722922	0,069208835	-0,386226007
LS2430-3	202,56	503	1,48321485	0,114450193	1,365647867
LS2726-3	725,03	503	-0,306235604	-0,856868625	-0,491235514
LS3238	2497,5	324	-0,87027027	-0,989812774	-0,895094784
LS3360	389,76	324	-0,168719212	-0,672442725	-0,327789468
LS3360-2	389,58	503	0,291134042	-0,678567607	0,061875449
LS3471-2	522,22	503	-0,036804412	-0,808201168	-0,082406587
LS4345	595,77	503	-0,155714454	-0,825439547	-0,195686873
LS4386	2002,8	324	-0,838226483	-0,983610016	-0,896723228
LS4436	558,76	324	-0,420144606	-0,750585083	-0,531103198
LS5001	165,63	503	2,036889452	-0,025896283	1,893108929
LS5120	825,07	503	-0,390354758	-0,902799854	-0,41921821

Table 9-7 Load Case 5 - E01-H/E02-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	1551,2	324	-0,791129448	-0,961555971	-0,833320398
LS328	1344,6	324	-0,759036145	-0,946489144	-0,805145934
LS2024	409,5	324	-0,208791209	-0,174903177	-0,360193462
LS2367	745,51	503	-0,325294094	0,119706941	-0,357237821
LS2430-3	195,15	503	1,577504484	0,156766749	1,455473389
LS2726-3	702,6	503	-0,284087674	-0,852299259	-0,474993574
LS3238	2934,7	324	-0,889596892	-0,991330427	-0,910723148
LS3360	377,77	324	-0,142335283	-0,662046421	-0,306454252
LS3360-2	377,58	503	0,332168017	-0,668352054	0,095623279
LS3471-2	505,64	503	-0,005221106	-0,80191206	-0,052318583
LS4345	575,21	503	-0,12553676	-0,819200151	-0,166937932
LS4386	2082	324	-0,844380403	-0,984233496	-0,900651912
LS4436	536,18	324	-0,395725316	-0,740081541	-0,511356677
LS5001	160,36	503	2,136692442	0,00611623	1,988186779
LS5120	808,06	503	-0,377521471	-0,90075375	-0,406992511

Table 9-8 Load Case 6 - E01-H/E02-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	1580	324	-0,794936709	-0,962256723	-0,836358609
LS328	1368,1	324	-0,763175206	-0,947408305	-0,808492963
LS2024	430,33	324	-0,247089443	-0,214841751	-0,391163114
LS2367	778,46	503	-0,353852478	0,072312928	-0,384444118
LS2430-3	208,46	503	1,412932937	0,082908141	1,298693427
LS2726-3	722,78	503	-0,304075929	-0,85642306	-0,48965174
LS3238	2964,9	324	-0,890721441	-0,991418734	-0,911632508
LS3360	388,24	324	-0,165464661	-0,671160305	-0,325157693
LS3360-2	388,04	503	0,296258118	-0,677291951	0,066089675
LS3471-2	508,84	503	-0,011477085	-0,803157798	-0,058278375
LS4345	593,89	503	-0,153041809	-0,824886963	-0,193140764
LS4386	2107	324	-0,846226863	-0,984420569	-0,901830698
LS4436	557,33	324	-0,41865681	-0,749945133	-0,5299001
LS5001	164,476	503	2,058196941	-0,019061756	1,913407621
LS5120	826,86	503	-0,391674528	-0,903010275	-0,420475495

E03-H

Table 9-9 Geometric considerations and Buckling Tension of Channel sections for E03-H

PART NO.	A (m)	Iyy (m^4)	Izz (m^4)	Buckling Force (N)	Buckling Tension (Pa)
LS264	1,15E-04	2,56E-08	4,02E-09	1,09E+04	9,499679E+07
LS328	1,51E-04	1,71E-08	6,35E-09	1,73E+04	1,146165E+08
LS2024	2,67E-04	4,33E-08	5,27E-08	1,43E+05	5,382339E+08
LS2367	2,11E-05	4,81E-08	1,05E-08	2,80E+04	1,329750E+09
LS2430-3	6,01E-04	1,89E-07	8,10E-08	2,16E+05	3,596057E+08
LS2726-3	2,10E-04	8,29E-08	1,30E-08	3,47E+04	1,653115E+08
LS3238	9,47E-05	4,82E-09	1,41E-09	3,84E+03	4,052973E+07
LS3360	3,63E-04	2,15E-07	2,71E-08	7,38E+04	2,033746E+08
LS3360-2	3,63E-04	2,15E-07	2,71E-08	7,24E+04	1,994796E+08
LS3471-2	3,02E-04	1,15E-07	1,81E-08	4,83E+04	1,595555E+08
LS4345	2,65E-04	7,13E-08	1,64E-08	4,39E+04	1,656673E+08
LS4386	1,15E-04	3,71E-08	2,22E-09	6,03E+03	5,229117E+07
LS4436	2,68E-04	4,73E-08	2,19E-08	5,94E+04	2,220036E+08
LS5001	6,87E-04	7,02E-07	6,62E-08	1,77E+05	2,570138E+08
LS5120	2,12E-04	2,58E-08	1,01E-08	2,70E+04	1,277527E+08

Table 9-10 Load Case 1- E03-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	177,93	324	0,820940819	-0,467489168	0,453118634
LS328	150,99	324	1,145837473	-0,239751016	0,7352194
LS2024	52,661	324	5,152560719	9,188661435	3,97523361
LS2367	93,61	503	4,373357547	13,19347739	4,118957717
LS2430-3	28,388	503	16,7187544	11,66473944	15,87986585
LS2726-3	90,377	503	4,565575312	0,828494348	3,081453414
LS3238	212,48	324	0,524849398	-0,809219142	0,233060886
LS3360	51,103	324	5,340136587	2,979449497	4,126915781
LS3360-2	50,729	503	8,915432987	2,932740555	7,154811599
LS3471-2	66,095	503	6,610257962	1,41639548	6,249952824
LS4345	74,084	503	5,789590195	1,23805792	5,4681393
LS4386	209,76	324	0,544622426	-0,750783359	-0,01390771
LS4436	67,806	324	3,7783382	2,271937962	2,863976302
LS5001	22,596	503	21,26057709	10,40044364	20,20665746
LS5120	97,931	503	4,136269414	0,302396535	3,893094443

Table 9-11 Load Case 2- E03-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	179,61	324	0,803908468	-0,472470061	0,439526744
LS328	152,47	324	1,125008198	-0,247130622	0,718375924
LS2024	53,268	324	5,082451002	9,072559507	3,918539783
LS2367	94,495	503	4,323032965	13,06054732	4,071015735
LS2430-3	28,653	503	16,55488082	11,54760839	15,72375081
LS2726-3	91,22	503	4,514141636	0,811596511	3,043735093
LS3238	214,03	324	0,513806476	-0,810600772	0,22413109
LS3360	51,402	324	5,303256683	2,95630146	4,097093054
LS3360-2	51,096	503	8,844214811	2,904493416	7,096239189
LS3471-2	66,66	503	6,545754575	1,395914481	6,188503328
LS4345	74,764	503	5,727836927	1,217702142	5,40930972
LS4386	211,51	324	0,531842466	-0,752845337	-0,02206648
LS4436	68,464	324	3,732414115	2,240491725	2,826840049
LS5001	22,692	503	21,16640226	10,35221331	20,1169413
LS5120	98,879	503	4,087025556	0,28990984	3,846182019

Table 9-12 Load Case 3 - E03-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	179,03	324	0,809752555	-0,470761033	0,444190351
LS328	152,44	324	1,125426397	-0,246982458	0,718714098
LS2024	53,544	324	5,051098162	9,020639097	3,893186485
LS2367	87,795	503	4,729255652	14,13356591	4,458005944
LS2430-3	29,872	503	15,83851098	11,03557255	15,04129726
LS2726-3	89,134	503	4,643188907	0,853993243	3,138370489
LS3238	215,18	324	0,505716145	-0,81161299	0,217588889
LS3360	50,687	324	5,392171563	3,012109765	4,168993571
LS3360-2	53,339	503	8,430248036	2,74030251	6,755777903
LS3471-2	66,52	503	6,561635598	1,400956995	6,20363247
LS4345	71,606	503	6,024551015	1,315508239	5,691975978
LS4386	210,17	324	0,541609174	-0,751269531	-0,01583138
LS4436	68,53	324	3,727856413	2,237370866	2,823154489
LS5001	24,888	503	19,21054323	9,350547428	18,25368177
LS5120	99,007	503	4,080448857	0,288242195	3,839916692

Table 9-13 Load Case 4- E03-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	179,5	324	0,805013928	-0,472146784	0,440408905
LS328	152,68	324	1,122085407	-0,248166138	0,716012426
LS2024	53,497	324	5,056414378	9,029442769	3,897485413
LS2367	94,481	503	4,323821721	13,06263078	4,071767148
LS2430-3	28,642	503	16,56162279	11,55242732	15,73017359
LS2726-3	91,016	503	4,526500835	0,815656958	3,052798576
LS3238	215,05	324	0,506626366	-0,811499108	0,218324934
LS3360	50,944	324	5,359924623	2,991869654	4,142917265
LS3360-2	50,652	503	8,930506199	2,938719016	7,167208355
LS3471-2	66,517	503	6,561976638	1,401065281	6,203957362
LS4345	74,722	503	5,731618533	1,218948676	5,412912287
LS4386	210,98	324	0,535690587	-0,752224463	-0,019609827
LS4436	68,614	324	3,722068383	2,233407548	2,818474031
LS5001	22,542	503	21,31390294	10,42775372	20,25745861
LS5120	99,115	503	4,07491298	0,286838471	3,834642908

Table 9-14 Load Case 5- E03-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	179,42	324	0,805818749	-0,471911424	0,441051156
LS328	152,37	324	1,126402835	-0,246636516	0,719503689
LS2024	53,254	324	5,084050024	9,075207492	3,919832823
LS2367	94,249	503	4,336926652	13,09724685	4,08425163
LS2430-3	28,146	503	16,87110069	11,77363118	16,02499936
LS2726-3	94,249	503	4,336926652	0,753374929	2,913776435
LS3238	213,15	324	0,520056298	-0,809818828	0,229184974
LS3360	91,537	324	2,539552312	1,221635051	1,862239063
LS3360-2	90,898	503	4,533675108	1,194811719	3,551095047
LS3471-2	66,131	503	6,606115135	1,415080057	6,246006137
LS4345	74,407	503	5,760116656	1,228342534	5,440061175
LS4386	210,4	324	0,539923954	-0,751541432	-0,01690723
LS4436	68,294	324	3,744194219	2,248558079	2,836365964
LS5001	22,024	503	21,83872139	10,69653216	20,75742971
LS5120	98,73	503	4,094702725	0,291856528	3,853495714

Table 9-15 Load Case 6- E03-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	178,23	324	0,817875778	-0,4683855	0,450672718
LS328	151,28	324	1,141723956	-0,241208395	0,731893027
LS2024	52,808	324	5,135434025	9,160299572	3,961384206
LS2367	93,712	503	4,367508964	13,17802863	4,113386032
LS2430-3	28,251	503	16,80467948	11,72615565	15,96172284
LS2726-3	90,441	503	4,561636868	0,827200426	3,078565199
LS3238	212,49	324	0,524777637	-0,80922812	0,233002857
LS3360	50,583	324	5,405314038	3,02035877	4,17962116
LS3360-2	50,578	503	8,945035391	2,944481703	7,179157689
LS3471-2	66,016	503	6,619365002	1,419287132	6,258628694
LS4345	74,097	503	5,788398991	1,237665263	5,467004492
LS4386	209,72	324	0,544917032	-0,750735825	-0,013719632
LS4436	67,888	324	3,77256658	2,267985881	2,859309114
LS5001	22,359	503	21,49653383	10,52128558	20,4314429
LS5120	98,084	503	4,128257412	0,300364943	3,885461766

E04-H

Table 9-16 Load Case 1- E04-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	38,615	324	7,390521818	1,453700694	5,695672627
LS328	35,323	324	8,172493843	2,249723807	6,41728554
LS2024	22,062	324	13,68588523	23,3198758	10,87565847
LS2367	30,508	503	15,48747869	42,55091841	14,70688449
LS2430-3	21,092	503	22,84790442	16,04563926	21,7188333
LS2726-3	28,595	503	16,59048785	4,779116408	11,8997907
LS3238	46,643	324	5,94637995	-0,130906743	4,617151065
LS3360	24,172	324	12,40393844	7,413114664	9,839019408
LS3360-2	23,561	503	20,34883918	7,467552124	16,5580594
LS3471-2	26,396	503	18,05591756	5,050600821	17,15372147
LS4345	27,228	503	17,47363009	5,089477118	16,5990022
LS4386	42,418	324	6,638266774	0,232393859	3,876295884
LS4436	25,779	324	11,5683696	7,606114491	9,163341369
LS5001	21,677	503	22,20431794	10,88376733	21,10571721
LS5120	31,244	503	15,09909103	3,082223628	14,3368849

Table 9-17 Load Case 2- E04-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	32,655	324	8,921910887	1,901535823	6,917727714
LS328	29,508	324	9,9800732	2,890131287	7,878974418
LS2024	16,707	324	18,39306877	31,11498772	14,68209596
LS2367	24,939	503	19,16921288	52,27605032	18,21430819
LS2430-3	16,043	503	30,35323817	21,41018658	28,86882951
LS2726-3	23,097	503	20,77772005	6,154774806	14,97045137
LS3238	40,333	324	7,033124241	0,005060789	5,495940722
LS3360	18,939	324	16,10755584	9,737726789	12,83392878
LS3360-2	18,012	503	26,92582723	10,0761712	21,96721284
LS3471-2	21,052	503	22,8932168	6,586531412	21,76200037
LS4345	21,814	503	22,05858623	6,600819793	20,96688511
LS4386	36,338	324	7,916285982	0,438595484	4,692187759
LS4436	20,389	324	14,89092158	9,881211706	11,85010433
LS5001	16,725	503	29,07473842	14,40235721	27,6508599
LS5120	25,636	503	18,62084569	3,975229952	17,69190326

Table 9-18 Load Case 3 - E04-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	28,645	324	10,3108745	2,30772045	8,026126671
LS328	25,339	324	11,78661352	3,530170647	9,339823085
LS2024	12,448	324	25,02827763	42,10291612	20,04762027
LS2367	20,633	503	23,37842291	63,39448548	22,22423457
LS2430-3	11,412	503	43,0764108	30,50426071	40,98962775
LS2726-3	18,799	503	25,75674238	7,79056512	18,6217626
LS3238	36,488	324	7,87963166	0,11097119	6,180464184
LS3360	14,429	324	21,45477857	13,09396408	17,15793036
LS3360-2	13,856	503	35,30196305	13,39838305	28,85605063
LS3471-2	16,597	503	29,30668193	8,622923377	27,87182213
LS4345	17,406	503	27,89808112	8,525697056	26,52991106
LS4386	32,449	324	8,984899381	0,611010592	5,374394243
LS4436	15,973	324	19,28422964	12,88950263	15,40272818
LS5001	11,913	503	41,22278183	20,62380797	39,22375824
LS5120	21,309	503	22,60504951	4,985498852	21,48747627

Table 9-19 Load Case 4 - E04-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	29,755	324	9,888926231	2,184327081	7,689410133
LS328	26,481	324	11,23518749	3,334805862	8,89391553
LS2024	13,48	324	23,03560831	38,80304895	18,43625943
LS2367	21,829	503	22,04274131	59,8663438	20,95179036
LS2430-3	12,827	503	38,21415764	27,028894	36,35757635
LS2726-3	19,964	503	24,19535163	7,277591349	17,47673388
LS3238	37,604	324	7,61610467	0,078000128	5,967364566
LS3360	15,722	324	19,60806513	11,9348561	15,66459593
LS3360-2	15,02	503	32,48868176	12,2825563	26,5423061
LS3471-2	17,867	503	27,15245984	7,938918637	25,81959097
LS4345	18,629	503	26,00091256	7,9003319	24,72256331
LS4386	33,591	324	8,645440743	0,55624074	5,157682677
LS4436	17,154	324	17,88772298	11,9332532	14,27345092
LS5001	13,488	503	36,29240807	18,09878591	34,52681138
LS5120	22,511	503	21,34463151	4,665896452	20,28673235

Table 9-20 Load Case 5 - E04-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	10,37	324	30,243973	8,136899932	23,93282531
LS328	7,415	324	42,69521241	14,48078139	34,33388768
LS2024	12,094	324	25,79014387	43,36456919	20,66369912
LS2367	9,176	503	53,81691369	143,7963621	51,2216251
LS2430-3	13,407	503	36,51771463	25,81633649	34,74145087
LS2726-3	9,979	503	49,40585229	15,56015971	35,96457713
LS3238	17,851	324	17,15024368	1,270859716	13,67709244
LS3360	12,033	324	25,92595363	15,90034137	20,77352091
LS3360-2	11,254	503	43,69521948	16,72738543	35,75896904
LS3471-2	10,879	503	45,23586727	13,68072978	43,04684547
LS4345	10,389	503	47,41659447	14,95959986	45,12432687
LS4386	14,224	324	21,7784027	2,675174543	13,54181094
LS4436	10,756	324	29,1227222	19,62635045	23,35856983
LS5001	14,146	503	34,55775484	17,21040749	32,87428474
LS5120	8,81	503	56,09421112	13,47729796	53,39110464

Table 9-21 Load Case 6 - E04-H

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	28,624	324	10,31917272	2,31014716	8,03274869
LS328	25,31	324	11,80126432	3,535361281	9,351670373
LS2024	12,34	324	25,2560778	42,48015396	20,23182959
LS2367	20,613	503	23,40207636	63,45696496	22,24676815
LS2430-3	11,466	503	42,86882958	30,355889	40,7918744
LS2726-3	18,763	503	25,80807973	7,807431312	18,65941029
LS3238	36,498	324	7,877198751	0,110666798	6,178496826
LS3360	14,431	324	21,45166655	13,09201079	17,15541384
LS3360-2	13,789	503	35,47835231	13,46834401	29,00111956
LS3471-2	16,596	503	29,30850807	8,623503211	27,87356181
LS4345	17,385	503	27,93298821	8,537203507	26,56316548
LS4386	32,467	324	8,979363662	0,610117433	5,370860221
LS4436	15,926	324	19,34409142	12,93049262	15,45113507
LS5001	12,029	503	40,81561227	20,41528177	38,83586598
LS5120	21,289	503	22,62722533	4,991121943	21,50860218

E05-Q/E06-Q

Table 9-22 Geometric considerations and Buckling Tension of Channel sections for E05-Q/E06-Q

PART NO.	A (m)	Iyy (m^4)	Izz (m^4)	Buckling Force (N)	Buckling Tension (Pa)
LS264	1,15E-04	2,56E-08	4,02E-09	4,95E+03	4,305271E+07
LS328	1,51E-04	1,71E-08	6,35E-09	7,83E+03	5,194441E+07
LS2024	2,67E-04	4,33E-08	5,27E-08	6,50E+04	2,439286E+08
LS2367	2,11E-05	4,81E-08	1,05E-08	1,27E+04	6,026452E+08
LS2430-3	6,01E-04	1,89E-07	8,10E-08	9,79E+04	1,629740E+08
LS2726-3	2,10E-04	8,29E-08	1,30E-08	1,57E+04	7,491946E+07
LS3238	9,47E-05	4,82E-09	1,41E-09	1,74E+03	1,836814E+07
LS3360	3,63E-04	2,15E-07	2,71E-08	3,34E+04	9,216974E+07
LS3360-2	3,63E-04	2,15E-07	2,71E-08	3,28E+04	9,040452E+07
LS3471-2	3,02E-04	1,15E-07	1,81E-08	2,19E+04	7,231082E+07
LS4345	2,65E-04	7,13E-08	1,64E-08	1,99E+04	7,508070E+07
LS4386	1,15E-04	3,71E-08	2,22E-09	2,73E+03	2,369845E+07
LS4436	2,68E-04	4,73E-08	2,19E-08	2,69E+04	1,006124E+08
LS5001	6,87E-04	7,02E-07	6,62E-08	8,00E+04	1,164791E+08
LS5120	2,12E-04	2,58E-08	1,01E-08	1,23E+04	5,789773E+07

Table 9-23 Load Case 1 - E05-Q/E06-Q

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	239,73	324	0,351520461	-0,820512611	0,078519161
LS328	213,46	324	0,517848777	-0,756609744	0,227399874
LS2024	98,834	324	2,278224093	1,467613739	1,650917469
LS2367	142,73	503	2,524136481	3,222226036	2,357287409
LS2430-3	47,614	503	9,564119797	2,422357144	9,06396505
LS2726-3	135,79	503	2,704249208	-0,449377527	1,716470397
LS3238	241,17	324	0,343450678	-0,923836377	0,086373832
LS3360	76,156	324	3,254425127	0,208524261	2,440316943
LS3360-2	75,423	503	5,669053207	0,198348324	4,484871161
LS3471-2	100,1	503	4,024975025	-0,27656498	3,78706925
LS4345	115,79	503	3,344071163	-0,350897552	3,138402555
LS4386	252,98	324	0,280733655	-0,906446754	-0,182375212
LS4436	113,57	324	1,852866074	-0,115342029	1,3069541
LS5001	32,798	503	14,33630099	2,549953603	13,61020891
LS5120	151,28	503	2,324960338	-0,615918621	2,167541194

Table 9-24 Load Case 2 - E05-Q/E06-Q

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	232,82	324	0,391633021	-0,8151855	0,110529158
LS328	204,41	324	0,585049655	-0,745833942	0,281741486
LS2024	95,135	324	2,405686656	1,563558483	1,753989353
LS2367	137,93	503	2,646777351	3,369160604	2,474121887
LS2430-3	45,706	503	10,00511968	2,56522367	9,484085938
LS2726-3	131,96	503	2,81176114	-0,43339629	1,795313089
LS3238	235,75	324	0,374337222	-0,92208534	0,111350062
LS3360	74,228	324	3,364929676	0,239914502	2,529675825
LS3360-2	73,157	503	5,875623659	0,235466539	4,654762191
LS3471-2	96,987	503	4,186262076	-0,253344824	3,940720219
LS4345	111,82	503	3,498300841	-0,327852151	3,28533028
LS4386	245,54	324	0,319540604	-0,903612038	-0,157600722
LS4436	109,26	324	1,965403624	-0,080444757	1,397956957
LS5001	32,185	503	14,62839832	2,617566514	13,88847699
LS5120	145,57	503	2,45538229	-0,600852984	2,291788362

Table 9-25 Load Case 3 - E05-Q/E06-Q

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	233,99	324	0,384674559	-0,816109612	0,104976275
LS328	205,18	324	0,579101277	-0,746787777	0,276931363
LS2024	94,818	324	2,417072708	1,572129092	1,76319662
LS2367	138,61	503	2,628886805	3,347726153	2,457078363
LS2430-3	45,777	503	9,988050768	2,559694018	9,46782515
LS2726-3	133,08	503	2,779681395	-0,438164821	1,771787761
LS3238	235,1	324	0,378136963	-0,921869923	0,114422702
LS3360	75,087	324	3,314994606	0,225729802	2,489296112
LS3360-2	74,452	503	5,756030731	0,213977135	4,556404631
LS3471-2	97,815	503	4,142360579	-0,25966523	3,898897223
LS4345	112,45	503	3,473099155	-0,331617853	3,26132176
LS4386	246,48	324	0,314508277	-0,903979633	-0,160813377
LS4436	109,4	324	1,961608775	-0,081621519	1,394888274
LS5001	32,752	503	14,35784074	2,554939492	13,63072887
LS5120	145,8	503	2,449931413	-0,60148264	2,286595555

Table 9-26 Load Case 4 - E05-Q/E06-Q

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	234,41	324	0,382193592	-0,816439095	0,102996453
LS328	205,25	324	0,578562728	-0,746874134	0,276495869
LS2024	94,844	324	2,416135971	1,571423983	1,762439133
LS2367	138,46	503	2,632818142	3,352436242	2,460823573
LS2430-3	45,713	503	10,00343447	2,56467773	9,482480517
LS2726-3	132,78	503	2,788221118	-0,436895424	1,778050273
LS3238	237,41	324	0,364727686	-0,922630129	0,103579365
LS3360	74,792	324	3,332014119	0,230564414	2,503058845
LS3360-2	74,011	503	5,796287038	0,221210707	4,589512878
LS3471-2	97,531	503	4,157334591	-0,257509453	3,913162296
LS4345	112,2	503	3,483065954	-0,330128588	3,270816683
LS4386	248,36	324	0,3045579	-0,904706474	-0,167165732
LS4436	109,21	324	1,966761286	-0,080023754	1,399054822
LS5001	32,607	503	14,42613549	2,570747945	13,69579023
LS5120	145,71	503	2,452062316	-0,60123649	2,28862557

Table 9-27 Load Case 5 - E05-Q/E06-Q

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	223,15	324	0,451938158	-0,807176734	0,158652917
LS328	192,55	324	0,682679823	-0,730178738	0,360689572
LS2024	87,201	324	2,715553721	1,796804352	2,004561612
LS2367	130,16	503	2,864474493	3,629980963	2,68151223
LS2430-3	42,075	503	10,95484254	2,872896329	10,38884449
LS2726-3	127,23	503	2,953470094	-0,412331796	1,899233791
LS3238	226,43	324	0,430905799	-0,918878324	0,157093924
LS3360	72,538	324	3,46662439	0,268802195	2,611910683
LS3360-2	71,895	503	5,996314069	0,257153149	4,75402236
LS3471-2	92,851	503	4,417281451	-0,220085454	4,160802058
LS4345	105,42	503	3,771390628	-0,287046363	3,545490722
LS4386	236,32	324	0,371022343	-0,899851472	-0,124734602
LS4436	100,82	324	2,213648086	-0,003465525	1,598698444
LS5001	32,498	503	14,47787556	2,582724422	13,74508068
LS5120	134,72	503	2,733669834	-0,568706717	2,556900474

Table 9-28 Load Case 6 - E05-Q/E06-Q

PART NO.	VMES [MPa]	Tensile Yield Strength [MPa]	Tensile MS	Buckling MS	Crippling MS
LS264	234,43	324	0,382075673	-0,816454755	0,102902352
LS328	205,35	324	0,57779401	-0,7469974	0,27587425
LS2024	94,794	324	2,417937844	1,572780305	1,763896208
LS2367	138,64	503	2,628101558	3,346785359	2,456330293
LS2430-3	45,752	503	9,994054905	2,561639121	9,473545023
LS2726-3	133,09	503	2,7793974	-0,438207036	1,771579496
LS3238	236,34	324	0,370906321	-0,922279847	0,108575684
LS3360	75,06	324	3,316546763	0,226170712	2,490551254
LS3360-2	74,258	503	5,77368095	0,217148666	4,570920811
LS3471-2	97,789	503	4,143727822	-0,259468391	3,900199735
LS4345	112,41	503	3,474690864	-0,331380015	3,262838109
LS4386	247,73	324	0,30787551	-0,904464134	-0,165047758
LS4436	109,31	324	1,964047205	-0,080865375	1,396860096
LS5001	32,764	503	14,35221585	2,553637476	13,62537028
LS5120	21,289	503	22,62722533	1,729288885	21,50860218

Table 9-29 Load Case 1(left) and 2 (right) - E07-V/E08-V

PART NO.	MATERIAL	VMES [MPa]	Tensile Yield Strength [MPa]	TensileMS
LS358	2024-T4	234,67	324	0,380662207
ls3200-4	7075-T6	319,34	503	0,578255151
LS3206-3	7075-T6	273,14	503	0,845207586
LS3208-3	7075-T6	325,98	503	0,546107123
LS3255	2024-T4	349,4	324	-0,07269605
LS3257-3	7075-T6	421,58	503	0,195502633
LS3378	2024-T4	281,73	324	0,15003727
LS3389	2024-T4	205,23	324	0,578716562
LS3399	2024-T4	209,16	324	0,549053356
LS3919	7075-T6	111,83	503	3,50684074
LS4222	2024-T4	448,36	324	- 0,277366402
LS4302	2024-T4	114,58	324	1,827718625
LS4439	7075-T6	227,86	503	1,21188449
LS4844	2024-T4	296,39	324	0,09315429
LS5252	7075-T6	304,45	503	0,103629496

PART NO.	MATERIAL	VMES [MPa]	Tensile Yield Strength [MPa]	TensileMS
LS358	2024-T4	243,66	324	0,329721743
ls3200-4	7075-T6	308,22	503	0,635195639
LS3206-3	7075-T6	276,5	503	0,82278481
LS3208-3	7075-T6	351,09	503	0,435529351
LS3255	2024-T4	444,3	324	- 0,270762998
LS3257-3	7075-T6	434,44	503	0,16011417
LS3378	2024-T4	284,18	324	0,140122458
LS3389	2024-T4	20825	324	- 0,984441777
LS3399	2024-T4	212,49	324	0,524777637
LS3919	7075-T6	117,85	503	3,276622826
LS4222	2024-T4	449,29	324	- 0,278862205
LS4302	2024-T4	120,06	324	1,698650675
LS4439	7075-T6	239,38	503	1,105439051
LS4844	2024-T4	365,82	324	- 0,114318517
LS5252	7075-T6	308,78	503	0,088153378

Table 9-30 Load Case 3 (left) and 4 (right) - E07-V/E08-V

PART NO.	MATERIAL	VMES [MPa]	Tensile Yield Strength [MPa]	TensileMS
LS358	2024-T4	238,57	324	0,358091965
ls3200-4	7075-T6	315,03	503	0,599847634
LS3206-3	7075-T6	270,95	503	0,860121794
LS3208-3	7075-T6	345,11	503	0,460403929
LS3255	2024-T4	436,98	324	- 0,258547302
LS3257-3	7075-T6	413	503	0,220338983
LS3378	2024-T4	278,97	324	0,161415206
LS3389	2024-T4	203,82	324	0,589637916
LS3399	2024-T4	207,8	324	0,55919153
LS3919	7075-T6	114,76	503	3,391774137
LS4222	2024-T4	441,9	324	- 0,266802444
LS4302	2024-T4	117,32	324	1,761677463
LS4439	7075-T6	234,39	503	1,150262383
LS4844	2024-T4	359,27	324	- 0,098171292
LS5252	7075-T6	301,03	503	0,116167824

PART NO.	MATERIAL	VMES [MPa]	Tensile Yield Strength [MPa]	TensileMS
LS358	2024-T4	237,45	324	0,364497789
ls3200-4	7075-T6	314,01	503	0,605044425
LS3206-3	7075-T6	269,7	503	0,868743048
LS3208-3	7075-T6	343,9	503	0,465542309
LS3255	2024-T4	435,56	324	- 0,256130039
LS3257-3	7075-T6	411,95	503	0,223449448
LS3378	2024-T4	277,86	324	0,166054848
LS3389	2024-T4	202,8	324	0,597633136
LS3399	2024-T4	206,61	324	0,568171918
LS3919	7075-T6	114,15	503	3,415243101
LS4222	2024-T4	440,64	324	- 0,264705882
LS4302	2024-T4	116,27	324	1,786617356
LS4439	7075-T6	233,24	503	1,160864346
LS4844	2024-T4	358,03	324	- 0,095047901
LS5252	7075-T6	300,34	503	0,118732104

Table 9-31 Load Case 5 (left) and 6 (right) - E07-V/E08-V

PART NO.	MATERIAL	VMES [MPa]	Tensile Yield Strength [MPa]	TensileMS
LS358	2024-T4	233,29	324	0,388829354
ls3200-4	7075-T6	293,12	503	0,719432314
LS3206-3	7075-T6	264,68	503	0,904186187
LS3208-3	7075-T6	349,28	503	0,442968392
LS3255	2024-T4	453,93	324	-0,28623356
LS3257-3	7075-T6	492,86	503	0,022602768
LS3378	2024-T4	271,8	324	0,19205298
LS3389	2024-T4	199,49	324	0,624141561
LS3399	2024-T4	203,31	324	0,593625498
LS3919	7075-T6	111,88	503	3,5048266
LS4222	2024-T4	457,78	324	-0,292236445
LS4302	2024-T4	114,23	324	1,836382737
LS4439	7075-T6	229,19	503	1,199048824
LS4844	2024-T4	349,55	324	-0,073093978
LS5252	7075-T6	322,05	503	0,043316255

PART NO.	MATERIAL	VMES [MPa]	Tensile Yield Strength [MPa]	TensileMS
LS358	2024-T4	237,07	324	0,366684945
ls3200-4	7075-T6	313,57	503	0,607296616
LS3206-3	7075-T6	269,29	503	0,871588251
LS3208-3	7075-T6	343,43	503	0,467547972
LS3255	2024-T4	434,93	324	-0,255052537
LS3257-3	7075-T6	411,46	503	0,224906431
LS3378	2024-T4	277,45	324	0,167777978
LS3389	2024-T4	202,49	324	0,600079016
LS3399	2024-T4	206,33	324	0,570300005
LS3919	7075-T6	113,66	503	3,43427767
LS4222	2024-T4	439,93	324	-0,263519196
LS4302	2024-T4	116,15	324	1,789496341
LS4439	7075-T6	232,89	503	1,164111812
LS4844	2024-T4	357,46	324	-0,093604879
LS5252	7075-T6	299,34	503	0,122469433