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Structural Analysis for VVIP Cabin Compartment Modification STC of Commercial Airplane

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Abstract

This paper presents a study on the design and structural substantiation of the interior structure of the new VVIP aircraft. In this study, the structural design and analysis of the compartment with aluminum alloy and sandwich composite panel were performed. The structural design requirements from the Federal Aviation Administration were identified. The structural analysis of the compartment was performed by the utilization of the finite element analysis method, for the structural design process. Therefore, the designed cabin compartment secured the structural integrity, and satisfied its certification standards and design requirements via structural analysis.

Key Words: Structural Analysis, Finite Element Method, VVIP Cabin Interior Compartment, Supplemental Type Certificate

1. Introduction

Driven by the development of airline-related industries and exploitation of novel technologies, the airplanes with applied advanced techniques have been developed. With this background, airplane manufacturing became more efficient, and the reduction of the airplane weight using new materials was actualized, resulting in more advantages for airlines, including reduced operation cost and higher attraction of customers. Therefore, the number of customers using the airplane has increased and is diversified. Airplane purchasers are also increasing and being diversified, including not only global full service carriers operating airplanes, and Low Cost Carrier (LCC) focused on short-haul, but also specific organizations, companies, and individual customers. With an increase in these purchasers, airplane interiors were required to be improved, to meet the needs of those clients, leading to the emergence of companies specializing in interior renovation. Moreover, existing airplane manufacturers started to pioneer the VVIP airplane market solitarily to satisfy the needs of customers, as presented in Fig. 1. The Boeing Business Jet (BBJ) for the Boeing Company, and Airbus Corporate Jet (ACJ) for the Airbus Company are the departments in charge of the development [1]. To reflect the demand of the customer directly in the airplane cabin interior compartment, various and numerous design elements are accompanied, and the resultant technical difficulties arise. This ultimately results in a higher cost for customers, hence, the corresponding field is regarded as a higher value-added business, and the airplane manufacturers or airlines pay a lot of attention to it.

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Fig. 1 VVIP Aircraft Interior Compartment

The interior structural design of the airplane cabin requires a complex understanding of several elements such as certification, safety, material, design, manufacturing technique, and engineering. Because such elements are important parts that customers, who have ordered their airplanes, first experience while using, high quality is required. Although this special interior compartment is sometimes designed by the airplane manufacturer, in several cases, the airplane manufacturer collaborates with companies specializing in the airplane interior, to perfectly reflect the requirements of the customer.

This study designed and analyzed the structure with the most significant structural effect when renovating the cabin interior of the Airbus A319 by an interior company at a customer's request, to use it as a VVIP airplane.

2. Results and Discussion

2.1 Definition and Procedure of the Supplemental Type Certificate

The general procedure that the airplane manufacturer conforms to when developing a new airplane is classified into three elements, i.e., design, production, and operation, as presented in Fig. 2. The airframe, engine, and propeller can be divided into type certificate, production certificate, airworthiness certificate, and operation certificate.

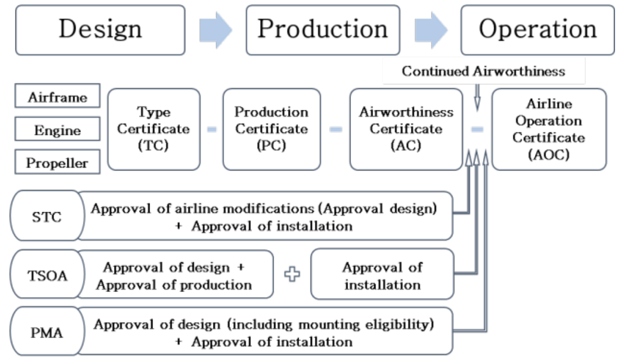

Fig. 2 General Certification Process

Unlike this general procedure, the Supplemental Type Certificate (STC) required for mounting the new airplane interior is a technical evidence, that the design modifications of the product that have received the Type Certificate (TC) for the corresponding part from the Federal Aviation Administration (FAA), satisfy the related regulations, and meet the technical criteria, and its procedure is illustrated in Fig. 3.

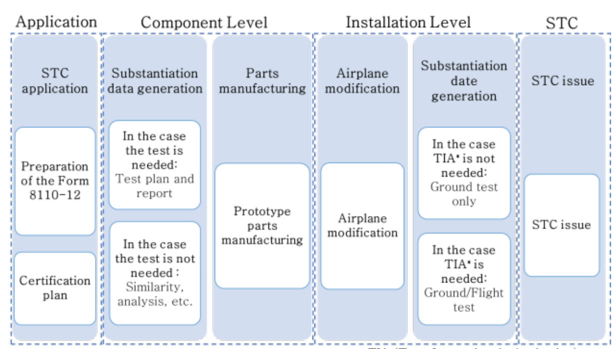

Fig. 3 STC Process Flow Chart

The STC generally defines the modification of this product design, divides the corresponding STC using the individual serial number, based on what impact it has on the existing type design, and identifies the certification standards by each number. This numbering system is uniformly managed by FAA, and can be identified through the internet site, or the office of the corresponding region. The systemized certification number and information included in the corresponding standards are useful information for identifying information already certified by other STC applicants, identifying the compatibility for the product, and preventing the duplicate application.

The application process for the STC is classified into four steps summarized in Fig. 3, which are: application, part manufacturing (component level), airplane modification (installation level), and STC issue. For application, the airplane certification plan, a certification plan on the airplane STC, is to be noted, to provide all the information and details of the renovation plan. As for the part manufacturing, depending on how to generate the compliance-proving data, the methods can be divided into two, namely: the method of generating the data through the test, and the method of composing the data using the analytical method, without any test, and this is the step where the technical data required for the proof of structural integrity or other certification items is generated.

The STC can be issued by the FAA Aircraft Certification Offices (ACO), or the representative of the FAA. The examples of being issued by a regional office include Designated Alteration Station (DAS), or Organization Designation Authorization (ODA) with Supplemental Type Certificate - Organization Designation Authorization (STC-ODA), DAS or STC-ODA follows the procedures approved by FAA when performing the STC project. The corresponding procedure is defined in the FAA Part 21[2-3].

2.2 Compliance

To ensure the compliance of the airplane cabin compartment for the certification items, it should satisfy the corresponding items for the design, analysis, test production, and certification processes that are demanded by certification authorities like FAA. The checklist of the STC process is presented in Table 1.

Table 1 STC Check List

1	Understanding of the Airplane Certification
2	Preparation of the Requirements Demanded by the Airplane Certification Authority
3	Preparation of the Standard Items for the Certification of the Manufacturer
4	Review of the Standards for Each Airplane Manufacturer and Airplane Type
5	Application of the STC Process -FAA STC Application Foam 8110 Preparation/Sending -FAA Project Familiarization Meeting -Certification Plan Preparation/Sending -No Objection Official Letter of FCAA (Foreign Civil Aviation Authority)
6	Component Level Verification -MDL(Master Drawing List) Preparation -Execution of the Analysis -Execution of the Tests
7	Installation Level Verification
8	STC issue

The airplane cabin compartments closely related to safety should also guarantee the convenience and comfortability of the passenger. With regards to the cabin compartment design, the compliance to the items for the design, analysis, test, manufacturing, and certification processes, required by the certification authority like FAA can be demonstrated using one of the various methods illustrated in Fig. 4.

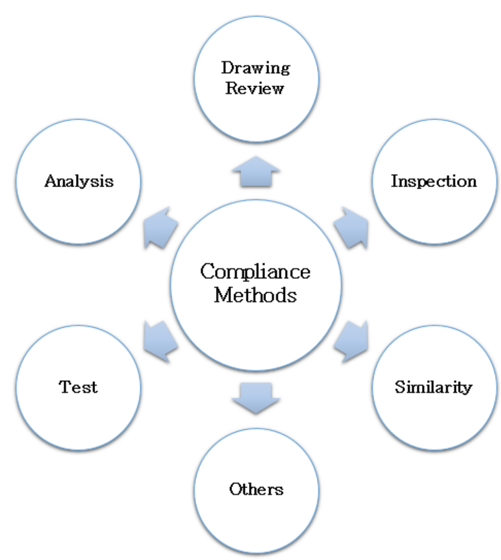

Fig. 4 Compliance Methods

In addition, it is required to identify the additional load requirements related to the emergency landing conditions, satisfy the requirements for the airplane cabin internal placement and design, and satisfy the ergonomic requirements. alongside the technical requirements including flammability and fire resistance conditions based on the certification items [5].

2.3 Design

Inside the VVIP airplane consists of structures in various shapes according to the demands of the customer, and the in-flight structures are composed of seat, galley, lavatory, cabinet, and in-flight entertainment system that is visually attestable, along with complex systems like ducting and wiring that are difficult to visually check and access[1]. For the displacement or design of the new structure inside the cabin, the shape information and corresponding part number of the existing structure need to be identified through the airplane manual or maintenance data, for securing the structure information of the corresponding airplane. The location where the structure is to be installed needs to be accurately identified on the Layout of Passenger Accommodation (LOPA), and the identification of the interference with surrounding structures should be performed.

In this study, the design and analysis of the Galley structure mounted at the rear of the airplane were performed. The corresponding structure is the largest and heaviest structure on board, and if it is damaged in specific circumstances, it can interrupt the emergency escape passageway along the airplane corridor, and can strike the bulkhead located at the front or passengers; thus, securing its structural stability is extremely important.

The structure materials were composed of sandwich composite panels and metal parts for weight reduction. The composite panels were assembled using hardware such as pins and inserts, which play a role in connecting the sandwich composite panels, and take charge of high load because of the location of the hardware and displacement of the structure. Therefore, based on the finite element model results, it is discovered that the concentrated stress phenomenon occurs at the connection part of the corresponding hardware. This is different from the actual behavior of the structure, resulting in a high load. After identifying the structural stability via detailed analysis, the reliability of the structural analysis was increased through the static load test, and the structural stability of the structure was reconfirmed.

By additionally equipping the upper and lower parts with fittings, it was designed such that the installation in the airplane body structure is easy. All fittings have the in-flight structure mountable spots in the airplane floor, seat track, and upper frame. In the panel storing the cart in the upper fitting of the structure, a large displacement value is generated in the Y direction on the airplane coordinate during the initial sizing process. Therefore, the design was modified by adding the fitting to the improved part of the lower fitting (Fig. 5) for taking charge of the load.

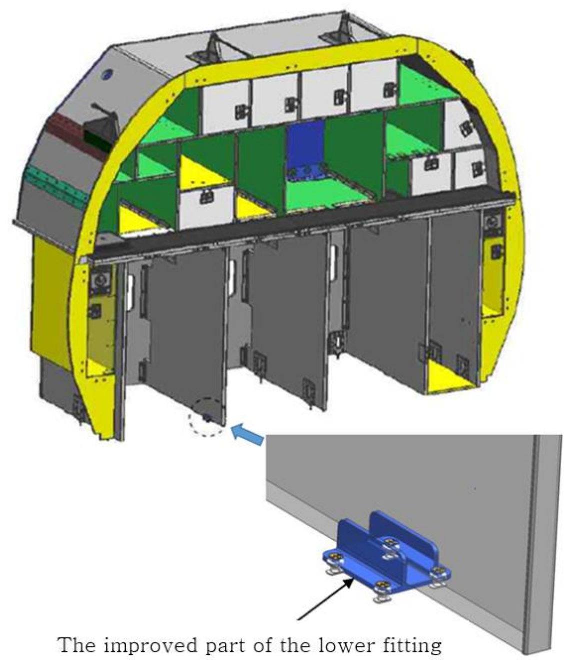

Fig. 5 Galley Structure Design and Modification [1]

For the upper fitting of the structure, the Tie Road mechanism was applied, as illustrated in Fig. 6 to design the concept that the airplane pressurization, or the movement of the airplane body and frame does not transfer the Z-directional load on the airplane coordinate. Among the load conditions, 9G forward directional emergency landing condition was identified to be the most severe load condition; hence, it was designed such that it bears most of the X-directional load on the plane coordinate, along with the lower fitting.

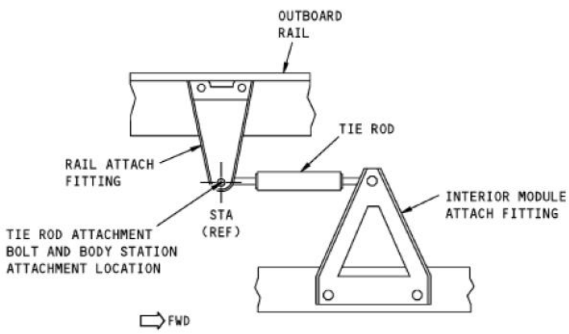

Fig. 6 Galley Structure Upper Attachment Design

The lower fitting was designed using the hardpoint provided by the airplane manufacturer. As illustrated in Fig. 7, the upper attachment fitting and surrounding structures were designed to bear the load in all directions, and the design was conducted using the machining parts, to enable the equipping and detaching of the structure in the case of repair or replacement, and to bear the high load[7].

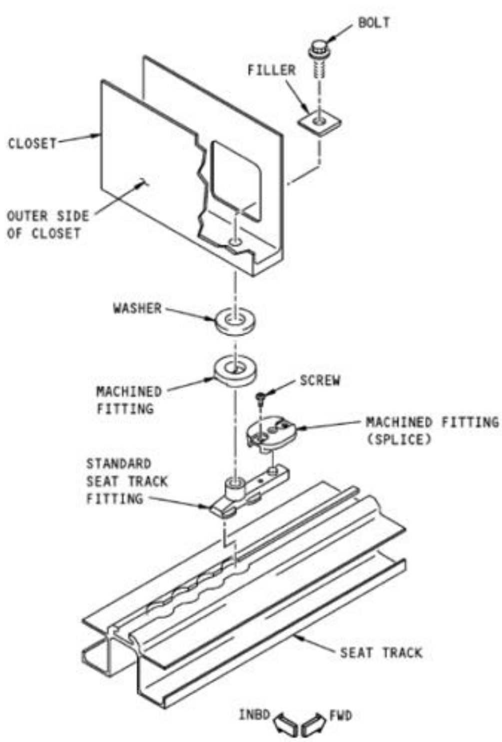

Fig. 7 Galley Structure Lower Attachment Design

2.4 Load

The load conditions for the cabin structure are based on the emergency landing load, as defined in FAR 25.561 presented below [4], and Table 2 indicates the load conditions required for the analysis.

Table 2 Emergency Landing Ultimate Load Factors

Direction	Load Factors
Forward	9.0 g
Afterward	1.5 g
Downward	8.6 g
Upward	5.4 g
Side (Port)	3.0 g
Side (Starboard)	3.0 g

Each airplane manufacturer considers the additional loads such as stepping, handling load, or abuse load, and utilizes them in the structural analysis. In this study, the analysis of the structures was performed, including the aforementioned loads.

2.5 Analysis

The structural analysis of the structures to be mounted inside the VVIP airplane was performed in conformity to the FAA regulations. The analysis methods for demonstrating the structural integrity of the structure can be mainly divided into three, as presented in Table 3. In general, if the structure is mounted at the cabin structure where the high load is applied, or the internal mounting structure is large or heavy, the structural integrity is additionally verified through the static test, and the structural stability of other structures is identified through the hand calculation, finite element model analysis, or comparative analysis method.

Table 3 Methodology of Structural Analysis [1]

No.	Analysis Method for Demonstrating the Structural Integrity
1	Stress Analysis Method (Hand Calculation, Finite Element Model)
2	Static Test Method
3	Comparative Analysis Method

In this study, the structural integrity demonstration was carried out via the structure-analyzing process, using the conventional hand calculation or finite element model, and the general analysis procedure, which is presented in Table 4.

Table 4 Structural Analysis Procedure

No.	Analysis Procedure for the Demonstration of the Structural Integrity
1	Composition of the Finite Element Model for the Interior Module
2	Calculation of the Interface Load for the Emergency Landing Load and Flight Load
3	Composition of the Floor Structure FEM
4	Entry of the Interface Load of All Interior Structures for the Floor Structure
5	Calculation of the Floor Structure Stress
6	Execution of the Stress Analysis
7	Preparation of the Structural Substantiation Report
8	Approval of the Structural Substantiation Report

Using the analysis method and procedure presented above, the analysis method was determined by analyzing the shape, load, and design data of the structure, the finite element model of the corresponding structure was composed to calculate the interface load of the structure, and the analysis of the structure was conducted based on them.

The results of the structural analysis were obtained utilizing the finite element model analysis simulation program. The FEMAP software was adopted as a pre-processor, and NEi NASTRAN as a post-processor.

As illustrated in Fig. 8, the sandwich composite describes the sandwich composite panel by applying the mid-surface of each panel applied in the design shape. In addition, the basic structure model was composed by applying the thickness and properties of each material to the plate element. The pins and inserts of the sandwich panel connection part were described using the bar element[10].

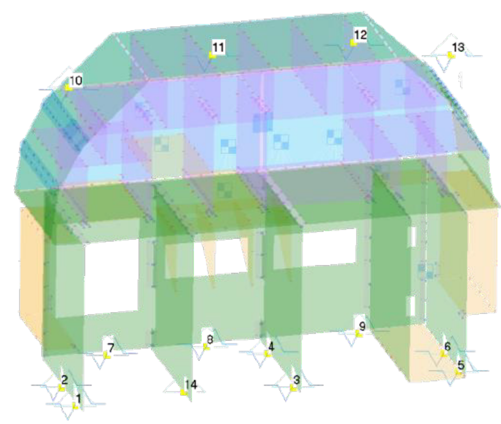

Fig. 8 Mid-Surfaced Model

The design was modified such that the lower fitting part transfers all loads in the direction of the X, Y, and Z axes according to the movement of the structure, using the design concept applied as the tightening area boundary conditions, and one of the lower vertical panels, where a large displacement value is generated additionally and takes charge of the Y-directional load.

The boundary conditions of the upper fitting part were set to be similar to those of the lower fitting. However, the Tie Road mechanism was applied in between the structure and the upper fitting, and the boundary conditions were set such that the Z-directional load is not transferred between the structure and airplane through the fitting.

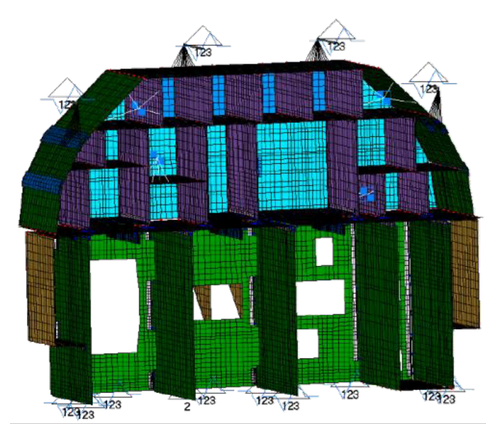

Fig. 9 Finite Element Model, Galley

For the analysis results of the structural deformation, the movement and corresponding displacement value for each load are presented in Fig.

10 and Table 5[7-8].

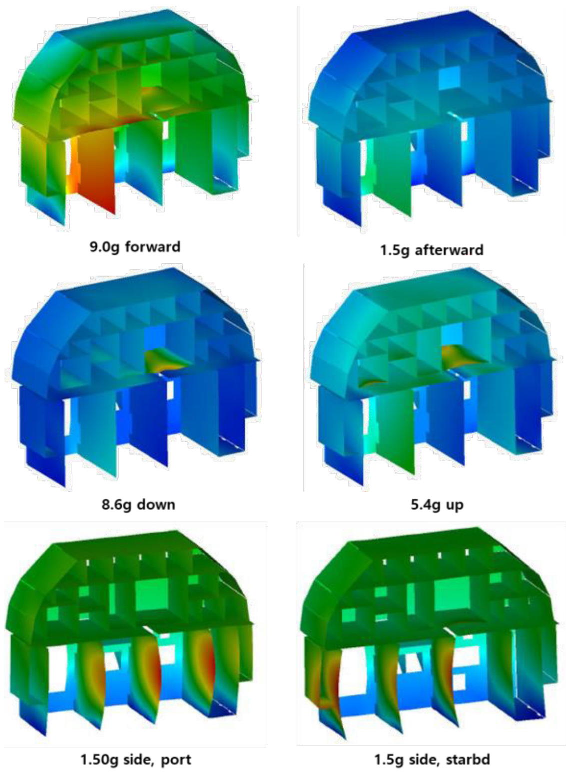

Fig. 10 Deformation Result

Table 5 Deformation Result

Load Case	Deformation (in)
9.0G Forward	0.70
8.6G Down	0.89
5.4G Up	0.58
3.0g Side, Port	0.67
3.0g Side, Starboard	0.73
1.5g Afterward	0.29

Based on the finite element model results, the most severe load condition was discovered to be the inertial force of the forward directional 9G, and the movement at the corresponding load is illustrated in Fig. 10. Based on the movement, it can be identified that the movement of the upper structure appears at the largest shelf, the box-shaped structure installed at the lower part delivers the load to the ¼ turn between the galley and box-shaped structure at the forward directional 9G load, and the concentrated load is transferred to the horizontal panel located at the center of the galley through the hardware, owing to the prying (Heel and Toe) movement, resulting in a large displacement value of the corresponding part. The structural integrity result of the corresponding part hardware was discovered to be +0.18, suggesting the safety margin was secured.

The lower fitting is an important load transfer medium connecting the main airplane structure and the internal structure, and Fig. 11 is the schematic diagram of the free body diagram. It can be identified that all directional loads of the airplane coordinate are transferred through the upper fitting, and for the detailed load values, the loads at the interface part calculated from the finite element model were adopted.

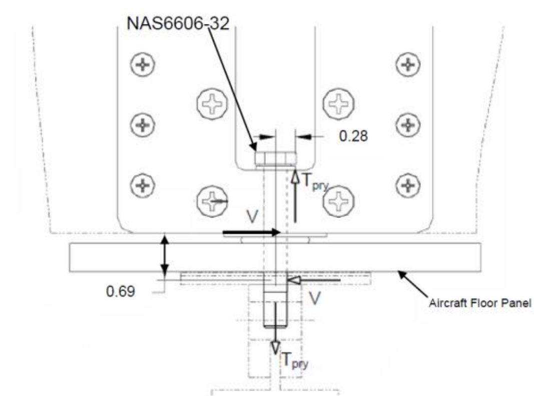

Fig. 11 Lower Fitting Structure

The allowed load value in each direction was provided by the airplane manufacturer (Table 6), and by calculating the load transferred to the lower fitting in each direction, the safety margin for the structure mounted part was obtained.

Table 6 Lower Fitting Allowable

Direction	Allowable (lb)	Reaction Load (lb)	Ratio
X	3500	2489	0.71
Y	2600	900	0.35
Z	6500	1824	0.28

In Eq. (1), using the ratio in each direction and fitting factor for the fastener (1.15), the safety margin is calculated to be +0.03[6]. This indicates the structural integrity of the upper mounting part.

$$\text{M.S.} = \frac{1}{1.15\times\sqrt{{R_x}^2 + {R_y}^2 + {R_z}^2}} - 1 \quad (1)$$

For the upper fitting part, as illustrated in Fig. 12, the structural analysis was performed on the main structure for the load transfer and upper fitting which connects the main airplane frames. It is the structure where the lug structure takes charge of the load of the fitting part, calculated using the finite element model, and the safety margin was calculated by dividing the load of the corresponding part, calculated using the finite element model into two.

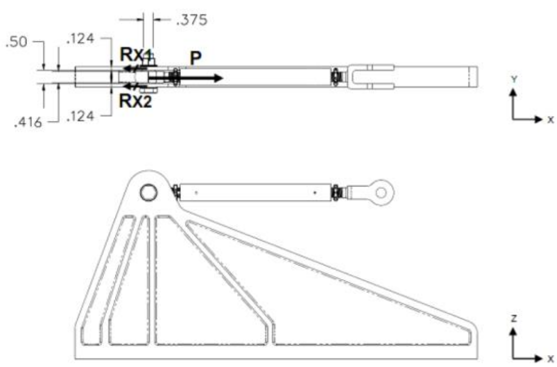

Fig. 12 Free Body Diagram, Upper Fitting

The allowed load value for the lug structure was calculated using the verified calculation program as illustrated in Fig. 13.

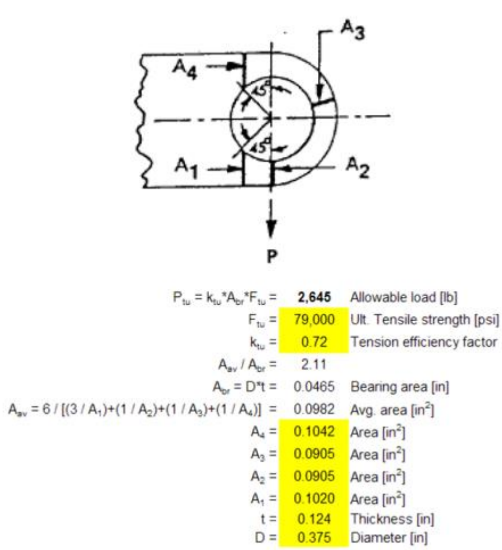

Fig. 13 Lug Allowable Calculation [9]

In Eq. (2), the safety margin for the lug allowable is +0.02.

$$\text{M.S.} = \frac{Lug\_allowable}{1.15 \times Applied\ Load} - 1 \qquad (2)$$

All the parts where pins and inserts connecting the composite panels (i.e., the main material utilized in the structure) were identified, and the part having the minimum margin was summarized. In terms of the panel pin, the maximum tensile load of 498 lb and shear load of 146.5 lb were identified at the bar element, where the pin (Element 9815) connecting the vertical and horizontal panels in charge of the main load at the side of the structure is installed (Fig. 14).

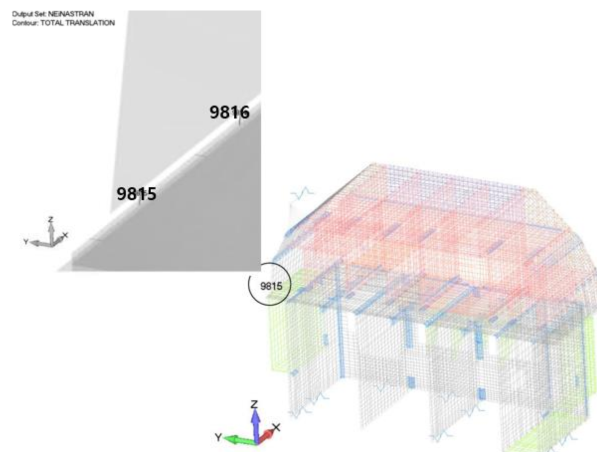

Fig. 14 Panel Pin Result

The maximum allowable load for the panel pin is illustrated in Table 7. After applying the fitting factor (1.15) and calculating the ratio for each direction, the safety margin was calculated to be +0.11, suggesting a sufficient structural strength margin.

Table 7 Panel Pin Allowable

Item	Tension (lb)	Shear (lb)
Panel Pin	659	691

As presented in Fig. 15, the insert (Element 2165) utilized at the part connecting the vertical and horizontal panel with the angle was found to transfer the largest load, and its structural integrity was verified. The maximum load that the insert was in charge of appeared to be the tensile load of 327 lb, and shear load of 540 lb based on the model results.

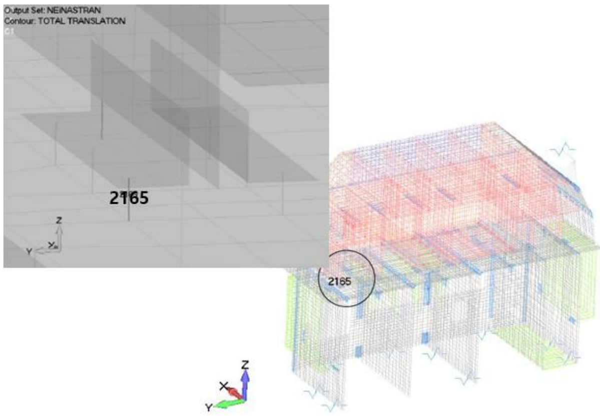

Fig. 15 Panel Insert Result

The maximum allowable load for the panel insert is presented in Table 8, and using the finite element model results for each direction, load ratio, and fitting factor (1.15), the safety margin is estimated to be +0.03.

Table 8 Panel Insert Allowable

Item	Tension (lb)	Shear (lb)
Panel Insert	621	816

For the analysis of the panel, only flexure bending and core shear in the failure mode were identified, owing to the characteristics of the sandwich composite panel. Based on the allowed value of the composite panel, the safety margin was calculated. The physical properties of the sandwich composite are tabulated in Table 9, and different properties were applied for different material thicknesses.

Table 9 Sandwich Composite Panel Properties

Thickness (in)	Flexure (in-lb/in)	Shear (lb/in)
0.500	288	51
0.750	439	56

On the basis of the structural analysis results, the maximum panel bending was obtained from the structure lower part where 0.75 inch-thick panel was used, and for the allowed value for the corresponding panel, 813 in-lb/in was applied (Table 9). Through Fig. 16, using the bending load of 748.2 in-lb/in identified in the model, the safety margin was calculated to be +0.08.

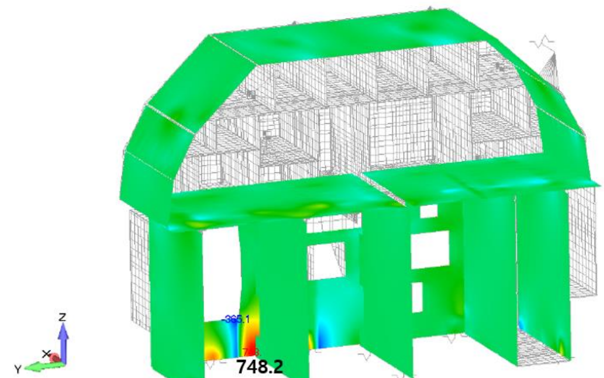

Fig. 16 Panel Flexure Bending Result

Based on the calculation results of the safety margin for the panel core front end, the maximum value was obtained from the panel with the heavy equipment mounted at the center of the structure (Fig. 17). The core shear allowed value of the panel used at the corresponding part is 56.0 lb/in as tabulated in Table 9, and in terms of the structural integrity, the maximum value of 46.9 lb/in was identified at the 9.0 G forward directional emergency landing load, indicating the safety margin of +0.19.

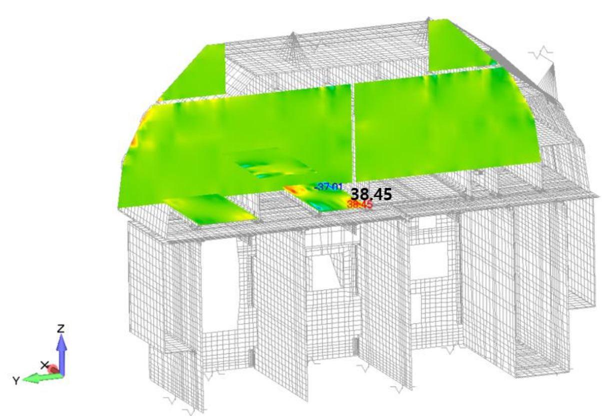

Fig. 17 Panel Core Shear Result

3. Conclusions

In this study, the design and analysis was performed on the cabin structure to be mounted inside the rear body of the commercial VVIP airplane. In conformity with the detailed procedure of the supplemental type certificate for the airplane alternation of the Federal Aviation Administration, the engineering process for the compliance certification was carried out.

The cabin structure is the structure where the emergency landing load is mainly applied. By analyzing the load in each direction, and using the hand calculation and finite element model, the stress and deformation analyses were performed on the structure with metal structure and mixed sandwich composite, and the optimized design model was deduced.

Based on the detailed structural analysis of each part, it was discovered to be a safe structure. To increase the reliability of the analysis, the regular interpretation test was conducted applying the same given loads, and each part was reviewed as a safe structure based on the test results.

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