An end-to-end airframe structural system design

B. P. Deepak*, T. Manojkumar, A. Prashanthan, R. Suresh, Philip K. Mathew, M. I. Junaidh, S. Rajendran, B. S. Raju and C. K. Krishnadasan

Vikram Sarabhai Space Centre/Indian Space Research Organization, Thiruvananthapuram 695 022, India

Design of aerospace reusable launch vehicle (RLV) structures offers diverse challenges due to stringent specifications in geometry, structural mass, integrity for thermal protection system and interfaces with propulsion, avionics and power systems. Airframe structures for RLVs should cater to the specified strength, stiffness and stability, and meet the functional and integration requirements of aerospace vehicles. To address these challenges, an integrated design cycle comprising load estimation, layout design, torsion box analysis and sizing of structural components is devised and presented. Verification of structural design is done by structural and thermo-structural analyses of the integrated airframe. Qualification of the airframe by integrated airframe test, thermo-structural test and acoustic test is also discussed.

Keywords: Airframe structure, integrated design cycle, reusable launch vehicle, thermal protection system.

Introduction

REUSABLE launch vehicle (RLV) is envisaged as a flying test bed of Indian Space Research Organization (ISRO) to evaluate advanced technologies in various areas of hypersonic re-entry vehicles, which is planned as the future space transportation system of India. RLV is a winged-body vehicle designed to fly from subsonic to hypersonic flight regime. Its configuration has a double-delta wing and aerodynamic control surfaces. In the hypersonic experiment mission of RLV, the vehicle has lifted off like a conventional launch vehicle and reached hypersonic speeds, and started its controlled descent using aerodynamic controls, but without propulsive power. Thus, the vehicle has experienced the flight environment of an upper stage in a launch vehicle during its ascent phase and then the flight conditions of an aircraft during its descent phase.

The structural design of RLV airframe demands an approach similar to that of aircraft design, while also taking care of the aero-thermal environment of hypersonic re-entry regime. This article presents an integrated approach for the structural design and analysis of airframe structures for winged body space vehicles. The load estimation for airframe, structural design procedure followed for the given specifications, structural analysis methodlogy adopted and qualification scheme for the airframe structures are described.

Load estimation for airframe

The external envelope for the fuselage, wing and vertical tail is defined based on aerodynamic considerations and mission profile for the vehicle. The critical loading events such as transonic, maximum dynamic pressure and longitudinal acceleration are defined by mission as in the launch vehicles. Besides this, the maximum allowable normal accelerations for the descending vehicle are defined from $V-n$ diagram taking care of the manoeuvrability requirements for RLV, where V is the equivalent velocity and n is the normal load factor. Figure 1 shows a typical $V-n$ diagram for RLV considering gust loads.

The external geometry of the airframe of RLV is modelled in CATIA software. The finite element (FE) model of this external geometry is generated from the CATIA model and the pressure coefficients are extracted at the surface coordinates from computational fluid dynamics (CFD) analysis results. The pressure coefficients are converted to surface pressure. Trim control forces are estimated and applied using in-house developed codes. Thrust, control force and pressure distribution are applied on the FE model. The forces and moments at salient stations along the vehicle and at attachment locations are extracted for equilibrium condition at all critical flight events.

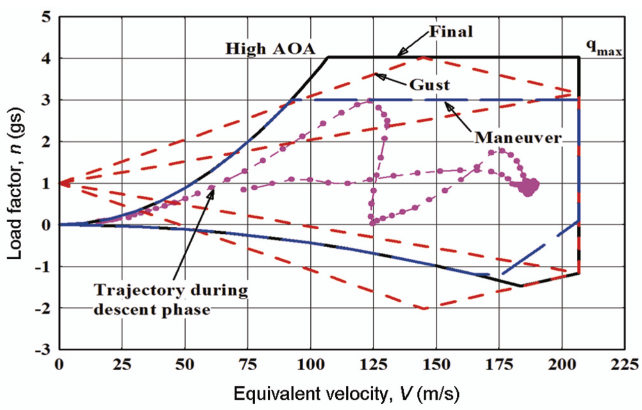

Figure 1. *V–n* diagram for reusable launch vehicle.

*For correspondence. (e-mail: bp_deepak@vssc.gov.in)

Design specifications for airframe

Structural loads

Critical load cases are defined during the flight regime of RLV based on mission requirements. The structure should have sufficient positive margin during the combined action of aerodynamic pressure, inertia loads, control surface loads and subsystem mounting loads. The skin panels should withstand pressure loads considering the differential pressure on the cabin.

Strength requirement

Under proof loads, no structural member should be stressed above the yield stress of the material, or there must be no permanent deformation or excessive deflection of any part of the structure that may interfere with the functioning of the system. Under ultimate loads, failure of the structure should not occur.

Stiffness requirement

For the structural integrity of the silica tiles, the panels are designed with a constraint such that deflection of the panel is limited to 1 mm for the given tile width. This is an important requirement, as excessive deflection may cause de-bonding of tiles from the panel.

Functional requirements

The design should facilitate mounting of subsystems, provision of cut-outs for accessing the packages and interfacing joints for vehicle integration.

Maintaining external profile accuracy

Being a hypersonic aerospace vehicle, the external aerodynamic contour should be smooth. Hence the external skin should avoid protrusions and panel deflection should be limited.

Mass budget and distribution

The structure should be designed with minimum mass, as it affects the primary mission objectives such as Mach number to be attained. The distribution is important as it governs the centre of gravity (c.g.) and consequently the stability of the vehicle.

Airframe structural design

The vehicle configuration consists of fuselage, wing and vertical tail as the main structural members, and elevons and rudders as the control surfaces. Fuselage cross-section varies from an ogive-shaped forebody to a flat-bottomed aft body. The wing is double delta in plan form having interfaces for leading edge and elevons.

Design approach

Due to the complex aerodynamic surface features, the design of RLV is conceived through a 3D model-based approach. The detailed 3D model of RLV is generated in CATIA (Figure 2). Airframe layout, interfaces, fastening scheme and design drawings of airframe components are extracted from this model. Fabrication drawings are made from the 3D model for the finalized design. The 3D model is also used as the input file for CNC machining of the airframe components owing to their complex geometric features. Interference studies of subsystems are also carried out using this model.

Layout design

Metallic envelope for airframe is extracted from the aerodynamic surface by subtracting thermal protection system volume. The structural layout of fuselage and wing, i.e. the positioning of bulkheads, longerons, spars and ribs is finalized based on stiffness, stability, functional, integration requirements and feasibility of manufacturing. The structural framework is covered with integrally stiffened panels, as they are structurally efficient, offer 10%–15% weight savings and reduce the number of joints in the assembly.

In the wing layout design, trade-off studies are carried out with different spar–rib layout configurations, considering load carrying capability and available design volume. The structural layout of RLV wing structure consists of two spars and four ribs, top and bottom panels and

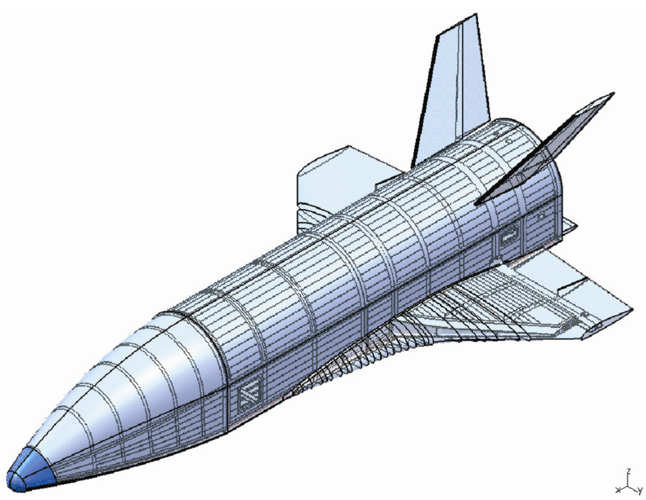

Figure 2. 3D model of RLV airframe.

wing-to-fuselage attachment lugs. The spacing of the spars is decided based on the leading edge chord length at the front spar and control surface chord length at the rear spar, and the requirement of accommodating the landing gear for future vehicles.

In the fuselage layout design, bulkheads and longerons are positioned considering the interfaces for wing and vertical tail attachment and other functional requirements. Longerons run through the length of the fuselage and act as splicers for panels. Cutouts are provided in the fuselage to provide access to packages. Figure 3 shows the structural layout of fuselage and wing.

Torsion box analysis

Unlike the axi-symmetric launch vehicle designs, the winged-body vehicles offer asymmetry in loads, which contributes to torsion and shear flow on the fuselage and wing structures. Fuselage, wings, vertical tails and the control surfaces are analysed as box structures with varying cross-section having stiffened panels and longitudinal stiffeners across the bulkheads and ribs[1,2].

The cross-section area of the stringer, longerons and spars is idealized as lumped area and placed appropriately on the skin. An effective skin width on each side of the stringer/longeron is considered with the area of stringer and assumed as carrying the same stress as the stringer. Axial and shear load distribution are calculated along the sections and stresses are estimated on members considering varying moments of inertia between two adjacent sections. Figure 4 shows the torsion box idealization for fuselage and wing, and the shear flow distributions.

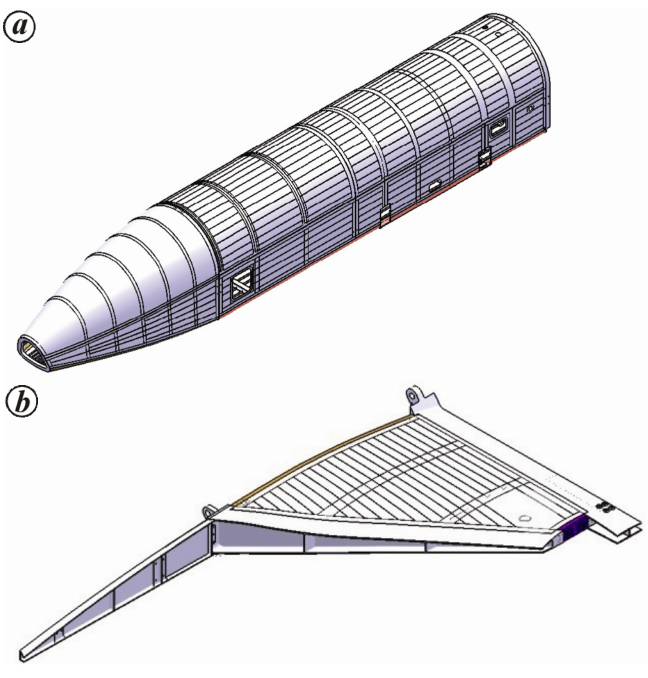

Figure 3. Airframe structural layout. ***a***, Fuselage; ***b***, Wing.

Material selection

Aluminium alloy is selected for the design of fuselage and wing as in aircraft due to high specific strength and stiffness and easy manufacturability. The thermal protection system (TPS) design ensures that the temperature at the TPS backwall-to-structure interface is limited to 393 K and hence permits the use of aluminium alloy for the airframe. Nose cap, vertical tails, elevons, rudders and leading edges are designed as hot structures. Nose cap is made of carbon–carbon, vertical tails and rudders are made of 15CDV6 steel with their leading edge made of Inconel-718, and elevons are made of titanium alloy. The leading edges of wings are made with 15CDV6 steel.

Sizing of structural components

Integrally stiffened panels are sized by an iterative design cycle considering shear flow and axial stress distributions and aerodynamic pressure across the panels for varying stringer spacings. Parametric studies are carried out with varying thickness and stringer spacing to limit the panel deflection within specifications (Figure 5). To arrive at optimum panel sizes for the given load intensity, effective length and material of the panel, Farrar's efficiency factor (F), which is a measure of the structural efficiency of skin–stringer panel is ensured to be maximum. Stiffened panels are ensured to have the required stiffness and also be free from panel flutter at ultimate aerodynamic pressure.

The bulkheads, longerons, spars, ribs and load diffusers are sized for the design loads, and margins are estimated against yielding and buckling strengths using interaction equations for axial, bending and shear stresses. Also, maximum von-Mises stress is computed for components and ensured to be less than yield for design. Bulkheads are designed as flat bottom in cross-section to extract the maximum volumetric efficiency and provide structural support to flat aerodynamic bottom surface of the vehicle. I-sections are preferred for bulkheads, spars and ribs to provide maximum structural efficiency. Longerons are designed to transfer axial loads as well as to act as splicers for connecting the panels. The loads coming from the wings are transferred by carry-through beams, whereas the load from the vertical tail are transferred through adjacent bulkheads. Loads from interstage are transferred through load diffusers provided in the aft end segment. Figure 6 shows a typical bulkhead and a rib obtained from design.

Interfacing joints on airframe

The wings and tails are attached to the fuselage structure using double shear lugs with shear pins to transfer moments as in-plane forces on the lugs. This removable

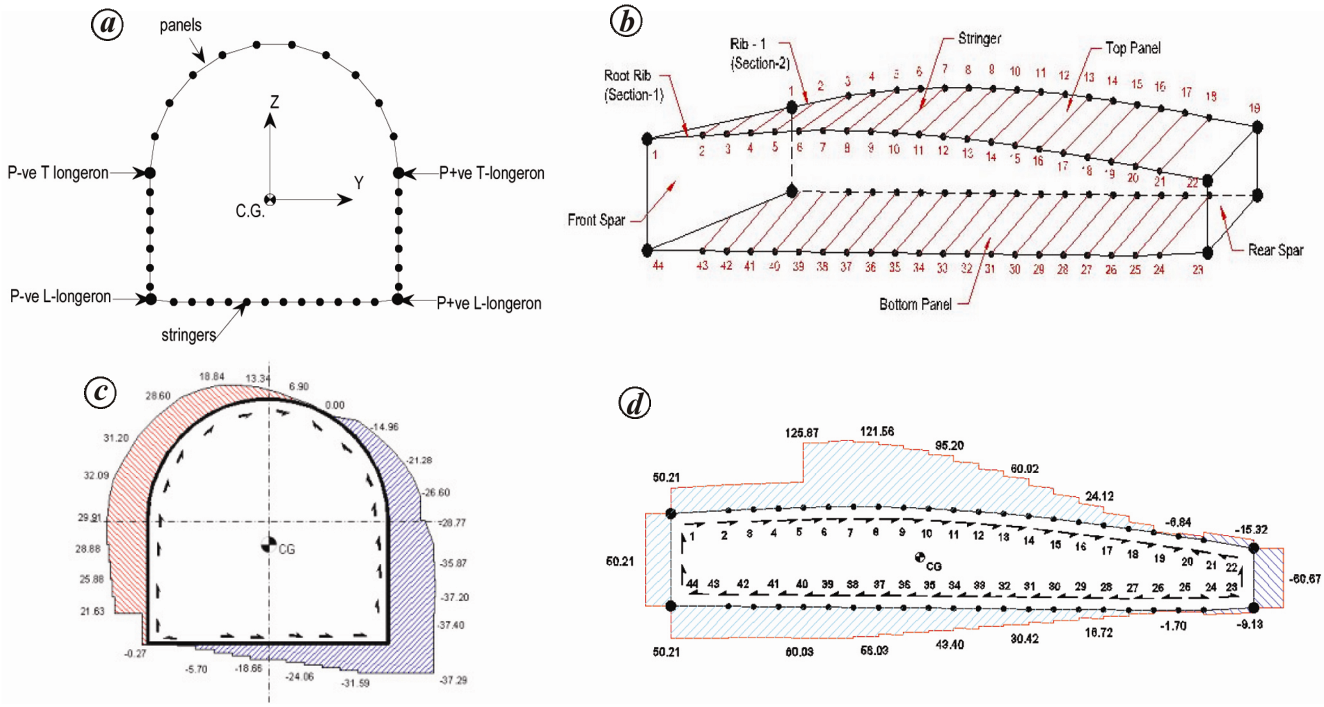

Figure 4. Typical shear flow diagram on bulkhead and rib. ***a***, Fuselage torsion box idealization. ***b***, Wing torsion box idealization. ***c***, Shear flow – fuselage box section, ***d***, Shear flow – wing box section.

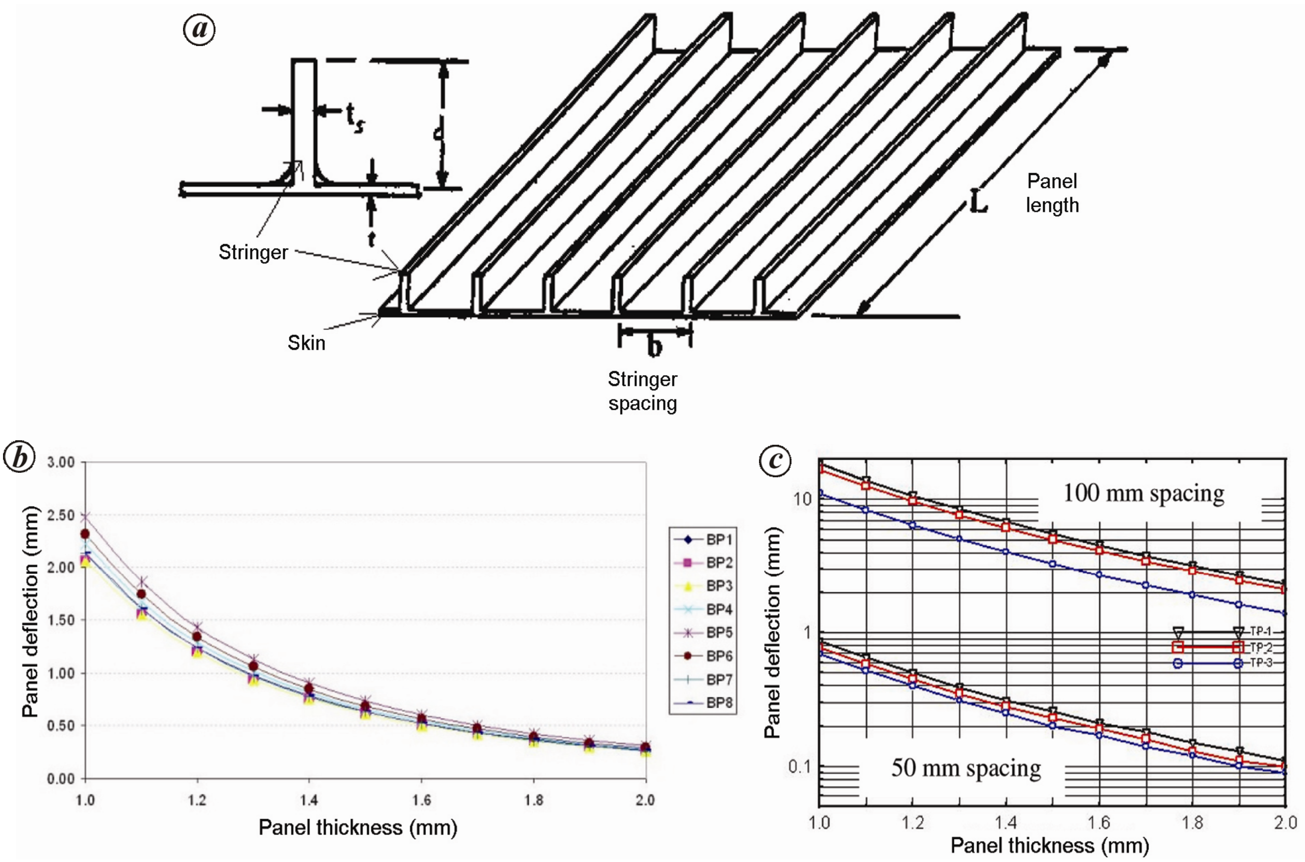

Figure 5. Integrally stiffened panel – parametric studies. ***a***, Integrally stiffened panel. ***b***, Panel deflection – varying thickness. ***c***, Panel deflection – varying stringer spacing.

joint design also facilitates easy handling of the wing and vertical tail assemblies. Bulkheads for wing attachment are designed to accommodate this joint with maximum lever arm between top and bottom pins (Figure 7 *a*). Similarly, aft bulkheads are designed for incorporating vertical tail–fuselage interfaces (Figure 7 *b*). These joints are analysed in detail and component-level qualification of the joint is also carried out.

Fasteners for airframe

Counter sunk rivets and screws are used on airframe panels for providing smooth external profile on the metallic airframe to facilitate efficient bonding of the TPS.

Airframe structural analysis

Airframe structural analysis is carried out using an integrated airframe model so as to simulate the adjoining structure interactions and flexibility of interface joints, which influence load transfer path. Detailed FE model of fuselage, wing and control surface structures is generated in a commercial FE analysis package. The bulkheads, longerons, spars, ribs, integrally stiffened skin, splicers, load diffusers, wing and vertical tail interfacing lugs are idealized using shell elements. All internal subsystems are modelled as lumped mass elements connected rigidly to fastener locations. Wing–fuselage shear pin joints and fasteners in the structure are modelled as beams with spider connections using multi-point constraints. The bearing connections are simulated in the model by releasing appropriate degrees of freedom for the elements. Total mass of the structure is simulated by smearing the equivalent TPS density on the fuselage and wing panels (Figure 8). All structural elements are assembled respecting the interfaces, and FE model of the integrated airframe is generated.

Detailed stress analysis is carried out with flight pressure distribution and corresponding inertia and actuator loads for all critical load cases. Design checks are carried out for the mounting schemes of sub-assemblies by considering the inertia loads due to static and dynamic accelerations. Minimum margin for each structural element is estimated from FE analysis of integrated airframe considering all load cases. Figure 9 *a–d* shows the deflection and stress contours for airframe structural components.

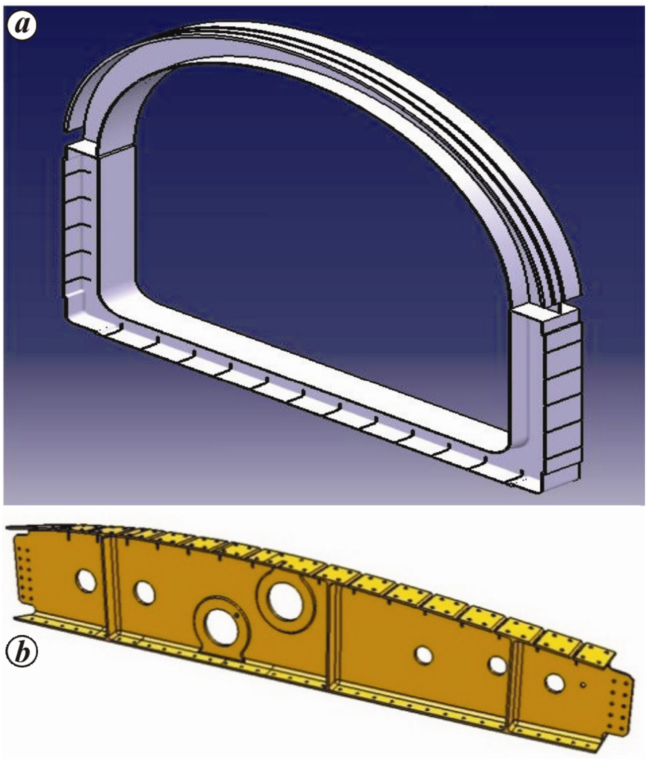

Figure 6. Sections: ***a***, fuselage bulkhead; ***b***, wing rib.

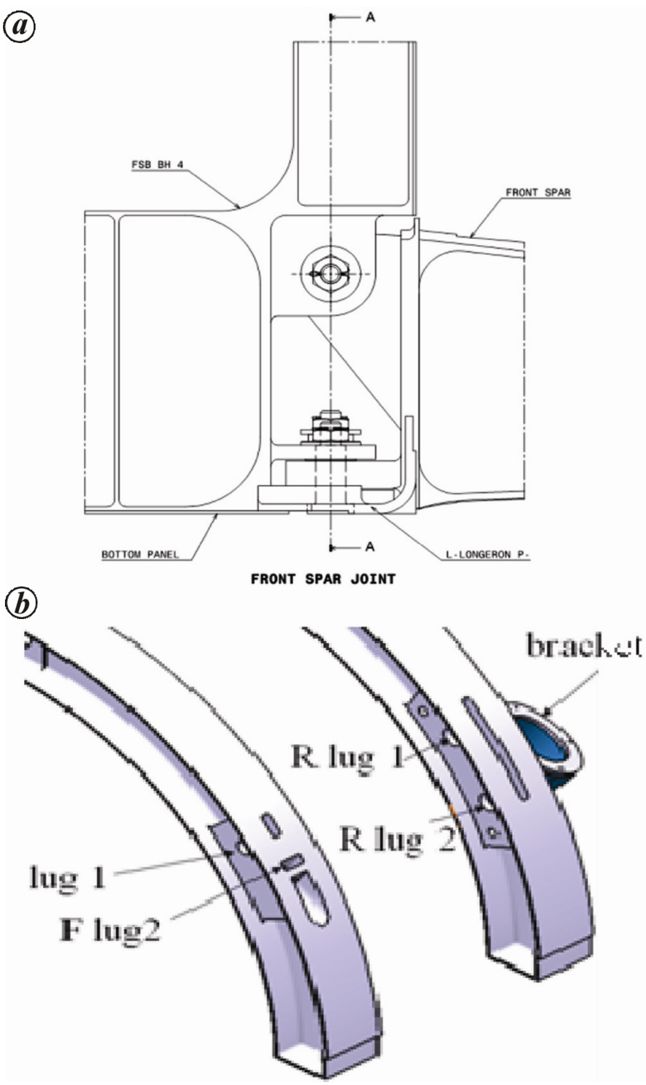

Figure 7. Wing and tail interface joints. ***a***, Wing spar joint; ***b***, Vertical tail – fuselage interfaces.

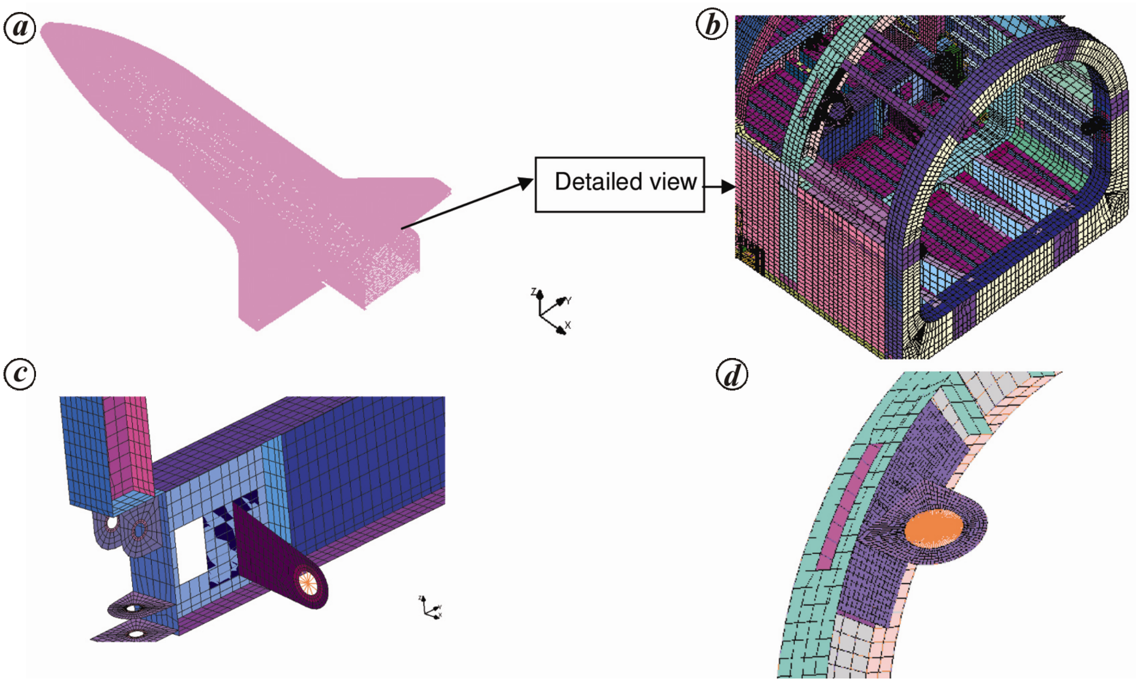

Figure 8. Finite element (FE) model of integrated airframe. ***a***, Integrated FE model – airframe. ***b***, Detailed view – fuselage aft segment. ***c***, Wing attachment lugs on bulkhead. ***d***, Vertical tail attachment on bulkhead.

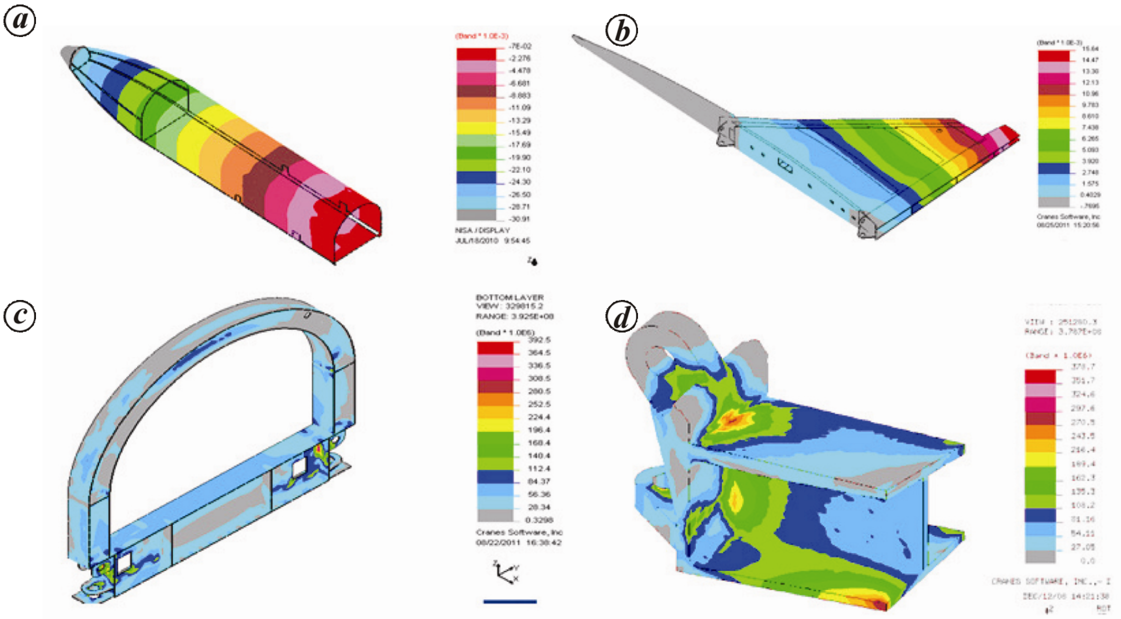

Figure 9. Results from FE analysis of integrated airframe. ***a***, Displacement contour – fuselage. ***b***, Displacement contour – wing. ***c***, Von Mises stress contour – bulkhead. ***d***, Von Mises stress contour – wing rear spar joint.

Buckling stability analysis is carried out on the integrated FE model of fuselage and minimum buckling load factors are estimated for fuselage. Moreover, the slope of deflection for each panel is computed from FE analysis displacement results and ensured to be within the constraints specified for the TPS system. Local modifications in the design are carried out at regions of high stress concentrations based on the results of integrated FE analysis.

Thermo-structural analysis

The nose cap, vertical tails, rudders, elevons and leading edges are subjected to very high temperatures during re-entry, and hence the design of these structures is validated through thermo-structural analysis. FE analysis is carried out for the combined thermal and mechanical loads for flight critical events. Figure 10 shows the temperature histories on the leading edge (made of Inconel 718) and other regions of the vertical tail (made of 15CDV6 steel). Figure 11 shows a typical stress contour on the vertical tail. Thermal buckling analysis of the structures is also carried out to ensure margin against buckling.

Qualification tests

Structural qualification tests

Structural qualification is intended to demonstrate the adequacy of the fuselage to withstand the design loads.

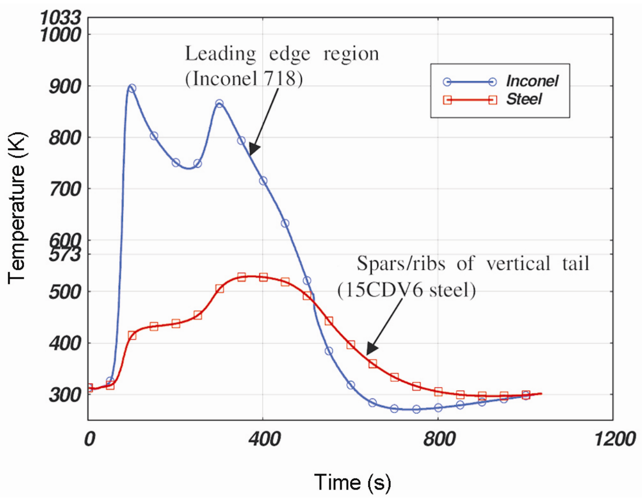

Figure 10. Temperature histories at different regions of vertical tail.

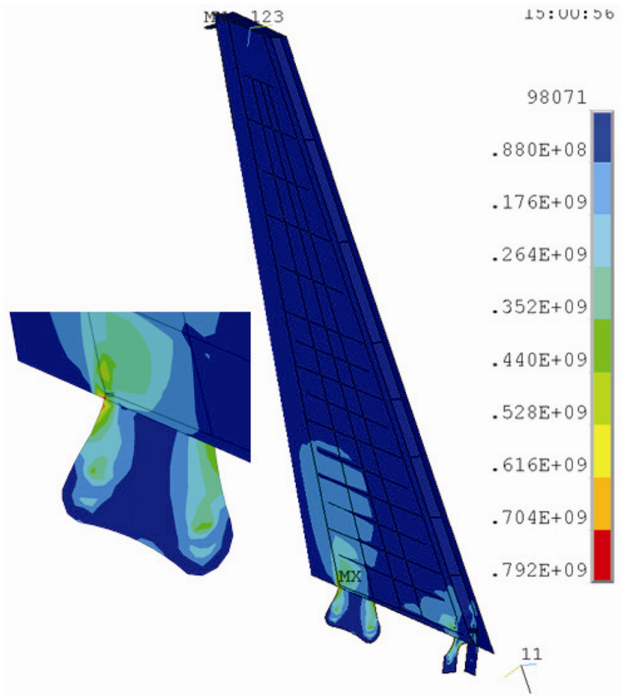

Figure 11. Thermo-structural analysis result: stress contour for vertical tail.

Fuselage and wing structures are qualified by an integrated airframe test with fuselage, wings and inter-stage structures assembled to the test rig structure. Vertical tails, rudders and elevons are not part of fuselage during the test. Reactions corresponding to loads on vertical tails, rudder and elevons are applied as reactions on the respective brackets.

The test is carried out by assembling the fuselage with the inter-stage in cantilever mode, where large deflections are expected (Figure 12). The airframe structure is primarily subjected to aerodynamic pressure distribution on the panel, in addition to inertia force. The net shear load on wings and fuselage is applied using a whiffle tree mechanism so as to reduce the number of loading jacks (Figure 13). The control surface actuator loads are also applied on the airframe interfaces in possible combinations as expected in flight. The loads acting on vertical tail, elevon, rudder and leading edge are applied as concentrated forces to simulate the loading requirement (Figure 14). Vacuum is also applied inside fuselage, after sealing the interfaces, to simulate panel stresses.

Figure 12. Fuselage static test set-up.

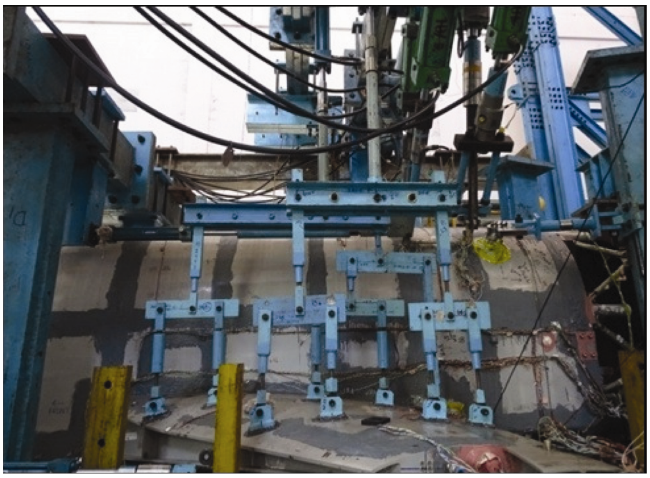

Figure 13. Whiffle tree mechanism on wings.

Figure 14. Vertical tail joint load application.

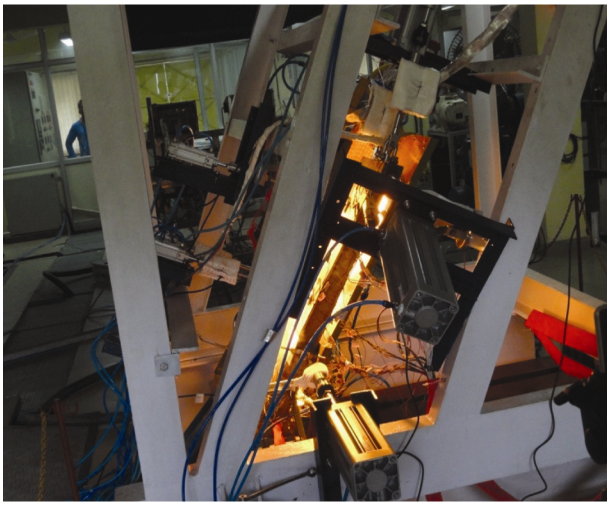

Figure 15. Thermo-structural test of vertical tail.

Loading lines are designed to take care of deflections at specific locations. The loads are effectively applied and controlled at multiple loading points using automated multipoint loading system (AMLS). This system consists of hydraulic power pack, hydraulic jacks, control system and load cells. Electrically operated proportional pressure control valve with spool position feedback through linear variable displacement transducer is used in the system to control the load within a very narrow limit. Loads on the structure are controlled by programmable logic control (PLC) system using PID control. AMLS applies the load based on feedback from load cells. These load cells are provided at suitable locations where loads are to be monitored during loading. AMLS is programmed to apply the loads gradually with an accuracy of ±1% for individual channels and +1% for total load. Apart from the AMLS system, an in-house developed 12-channel automated reconfigurable multi-parameter feedback control system is also used. With this system, loads are applied with very good accuracy.

Strain gauges are bonded at critical locations for monitoring strains developed due to applied loads. Displacement transducers (DTs) are used to monitor the structural deflections and joint openings.

Thermo-structural qualification tests

Thermo-structural qualification tests are carried out to qualify the nose cap, vertical tails, rudders, elevons and wing leading edges. Figure 15 shows a typical test set-up for vertical tail. Displacements and strains on the structure are measured and compared with the pre-test predictions. High-temperature strain gauges are used for measuring strains in hot structures. The strains measured are within acceptable material limits at the respective temperatures.

Acoustic test

During the ascent phase of flight, the vehicle is subjected to acoustic loading and associated vibratory loads. The TDV airframe in the assembled condition is qualified by an acoustic test, by subjecting it to an overall acoustic pressure level of 155 dB. The post-test inspections confirm that the airframe can withstand the levels satisfactorily.

Conclusion

An integrated approach for the structural design, analysis and qualification of airframe for a hypersonic re-entry vehicle is presented. Design of fuselage, wing and vertical tail structures of RLV for the given specifications is discussed in detail. Structural and thermo-structural analysis of the integrated airframe with subsystems using FE method is addressed. The qualification tests for airframe structure through integrated airframe tests, thermo-structural tests and acoustic test are also discussed.

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2. Bruhn, E. F., *Analysis and Design of Flight Vehicle Structures*, Jacobs Publishers, 1973.

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