

Historical Review of “Building Block Approach” in Validation for Human Space Flight

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ABSTRACT

The evolution of human spaceflight vehicles including launch vehicles continues to propose a perplexing conundrum in the structural dynamics field. Because of the size and weight of these vehicles, it becomes impossible to perform a ground based modal test that replicates all of the loading events of interest (i.e. liftoff, ascent, staging, etc.). As a result, human spaceflight programs have long relied on “building block approaches” to dynamic model updating and validation. Given the wide interpretation and definition of a “building block” approach to dynamic model validation, this paper reviews the state of art techniques used during the Saturn/Apollo and Space Shuttle dynamic test campaigns and contrasts them with the plans for the Space Launch System (SLS). Some of the lessons learned in each program are presented, in terms of how the building block approach was applied in developing models for stakeholders, using and updating analytical models, and use of other test result outside the dynamic tests.

Keywords: Building block approach, integrated system, element/component, scale model, ground vibration test, correlation

INTRODUCTION

Accurate prediction of the launch and flight loads is critical to the design and flight readiness verification of both the launch vehicle and its payload. Loads are a function of the structural dynamic properties of the coupled launch/space vehicle system. The structural dynamic properties, however, are a function of the design of the system. This, then, leads to an iterative design and verification process. Initially, estimated design loads size the structure. Analytical models are constructed, and coupled loads are computed. The design iterates, and the loads analyses repeated. The process converges to a design that has positive structural margins against predicted loads. Predicted loads are based on both the expected environment (e.g. forces) and the analytical models (e.g. the modal properties of the vehicle) and, hence, are likely to contain significant errors and uncertainties. Once hardware is built, uncertainties due to the latter can be reduced by performing a mode survey test where the dynamic properties of the vehicle are measured. The measured data are then used to adjust the analytical model.

The process reviewed so far would be adequate if the vehicle as a whole could be tested in every configuration of interest, i.e. mounted on the launch pad, early ascent stage with free boundary conditions and full fuel tanks, partially full tanks during ascent, after separation from stages or boosters, etc... Clearly the volume of testing that this would require is not feasible. Furthermore, some vehicles, such as the SLS, are too large and heavy to be tested as a whole with free boundary conditions. For these and other reasons, a modal testing and model updating/correlation are performed on subcomponents of these advanced vehicles. Then, testing and model updating must be performed for each subcomponent, and the boundary

conditions for each test and they must be selected so the component modes of vibration of each element are connected and the stiffness and damping of the interfaces must also be verified. Hence, the current building block approach may include tests on each subcomponent individually with free or approximately fixed boundary conditions, on assemblies of a few subcomponents, etc. The test-tuned subcomponent models are then used in a final prediction of launch and flight loads across a range of conditions. These loads, once compared with allowable values, establish the launch viability of the structural system for both the launch vehicle and its payload.

Launch and ascent structural loads are a function of the dynamic properties of the integrated launch vehicle/space vehicle system. Therefore, design changes in one element can result in load changes in all elements, and modeling errors in one element can result in load prediction errors in all elements. Since the dynamic properties of each element will be a function of the structural design of that element, the design process must be iterative. Flight attitude control and pogo analyses are also both dependent on the accuracy of the dynamic model, and failure of either analysis can result in loss of vehicle (LOV) or can severely degrade the ability of the vehicle to meet its flight objectives.

An important item to note is that neither the launch vehicle element organizations (e.g., core section, engines, boosters, second stage) nor the space vehicle organizations (e.g., Multi-Purpose Control Vehicle (MPCV)) control the overall structural dynamic properties of the integrated system since no organization controls the design and, thus, the properties of the other organizations' structure. This, therefore, makes the design of the flight elements (e.g., core section, engines, boosters, second stage) dependent on organizations typically not under the elements' control. This raises an important question. How can the various organizations have sufficient confidence in the quality of the models, and in the analyses performed by the other organizations, to commit to launch, or conversely, invest resources to redesign a system prior to launch?

For the latter, a substructuring approach is a possible alternative. Substructuring is the theoretical basis for the building block approach that can provide this confidence. There are two primary ways in which a substructured model of an assembly may be created. One could use the Hurty/Craig-Bampton (HCB) approach, in which case one can be assured that an assembly of HCB models will accurately predict the modes of an assembly (i.e. the dynamics of the vehicle) if the fixed-interface modes of each subcomponent are correct and if each subcomponent has a correct and complete set of constraint modes. The latter describe the stiffness of the interfaces between subcomponents. Hence, using the HCB mindset, testing should focus on assuring that the finite element model (FEM) captures these two types of modes accurately. Alternatively, one could use the Rubin method (or one of the many variants) in which case the free-interface modes of each subcomponent must be accurate as well as the residual attachment modes, which represent the static stiffnesses of the joints between the components. Either case provides a path whereby one can perform tests and correlate subcomponent models and gain assurance that the system level predictions will be correct.

It should be noted, however, that in modern practice we typically couple the full finite element (FE) models of each subcomponent to estimate response of the full vehicle, and so the models contain many modes (or additional degrees of freedom) that aren't fully validated by test. Similarly, each component cannot be tested in every possible configuration (i.e. fuel tank full, aerodynamic shells intact and jettisoned, etc...). However, by checking that the model faithfully reproduces the low frequency dynamics of each subcomponent, the interface stiffnesses, and that it is consistent with engineering drawings or the as built hardware, one can obtain significant assurance that the system level predictions will be accurate.

BUILDING BLOCKS AND THE INTEGRATED SYSTEM

As NASA embarks on the next evolution in space transportation, it is important to review major NASA program's approaches to low frequency structural testing and model validation and how the current programs within the NASA Human Exploration and Operations Mission Directorate (HEOMD) are approaching integrated dynamic testing. The common thread between the past and present is that each program used a building block testing approach to validate dynamic math models. The building block approach is a common term that defines a strategic test campaign designed to provide confidence and accuracy in modeling of the integrated design. D. B. Spaulding defined an analogous process in fluid dynamics as the "Art of Partial Modeling" [1]. The American Society of Mechanical Engineers (ASME) discuss a bottoms up approach to modeling [2] as an appropriate methodology for performing modeling verification and validation. In this approach a system is

decomposed into its constituent subsystems, elements, and components; thus, enabling validation experiments to be conducted at every level and leading ultimately to the system model validation. Figure 1 is an example of the ASME approach. The building block approach can manifest itself in many different forms and this paper examines case studies from the Saturn V development, the Space Transportation System (Shuttle), and the current integrated SLS. Each of these programs' processes culminates in a system level ground vibration test.

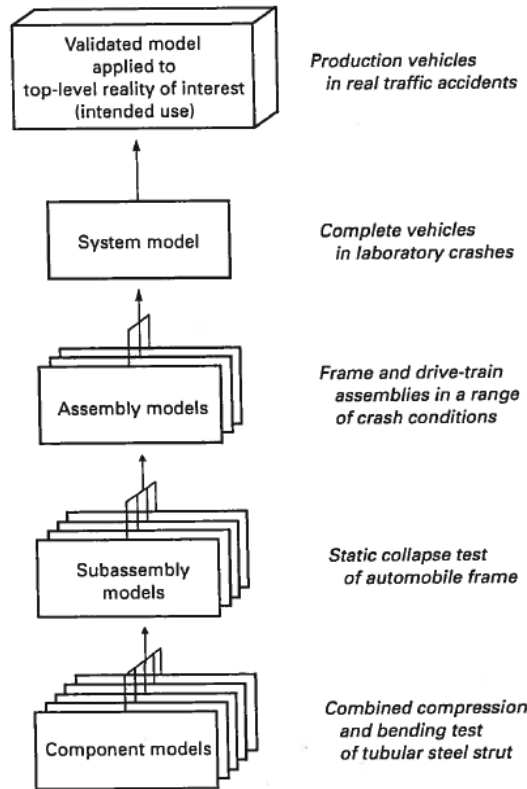


Figure 1. Example of Bottom-Up Approach to V&V [2]

Size, and hardware and organizational complexities of any complex system preclude validation at the system level except possibly for the lower order “beam bending” modes (i.e., modes with frequencies <10 Hz). Element/component models typically are updated/corrected/adjusted by element organizations making coupled system model correlation potentially complicated. Hence, mode survey tests and model correction/adjustment should be focused and performed at the element/component level. Elements/components should be responsible for delivering test-verified models that satisfy program success criteria. From these element/component models, coupled system loads analysis, pogo stability, and control stability models can then be developed for the appropriate configuration and time of flight.

The merits of performing an integrated system test are important enough from a technical perspective, but cannot provide the complete model validation for all phases of flights. In a ground vibration test (GVT) one can only measure the fundamental dynamic characteristics of the launch vehicles, and perhaps only for a few simulated for various phases of flight. While this provides important and provide data that is used to adjust pretest FEMs for use in verification loads analyses. However, element/component testing is equally as important because they contain important structural detail that is not exercised in the GVT and/or visible in the modes that can be extracted in that test as the validation of these models provide the basis for ascent integrated vehicle models. Without test-adjusted models, the model uncertainty factor (MUF) is not updated, and this uncertainty can translate into increased mass and vehicle instability due to incorrect modeling and boundary conditions.

Clearly, integrated system testing has considerable merit in that it allows for characterization of the entire system and exercises critical interfaces. This allows analysts to adjust/correct their idealized models and in particular any assumptions

regarding the interfaces, which might not be possible in the component level tests. However, an integrated system test is not the final answer since these results must be supplemented with comprehensive flight data. There are specific data that can only be captured during flight that cannot be captured on the ground. These data include system-level responses at flight pressurized levels and free-free vehicle characteristics.

SATURN V EXPERIENCE (1960'S)

The Saturn V program is the first notable program in human space flight to use a structural dynamic building block approach to validate the integrated vehicle characteristics. The program set forth four principles that were foundational in their approach: 1) Develop dynamic test and analysis program requirements; 2) Perform a scale model test campaign; 3) perform a full scale test campaign; and 3) develop a test validated system math model. These steps are one form of variant of a building block process.

At the beginning of the program, a 1/10th scale model of the Saturn V was created to assess math modeling techniques, validate test methods, and develop procedures for analyzing and testing the full scale article. The scale model simulated the dynamics of three vehicle boost phases. Water was used to simulate the liquid oxygen (LOX) and first stage fuel and the tanks were pressurized to an equivalent flight pressure. Results from the 1/10th scale testing and the full scale testing are shown in Figures 2 and 3 for the first two pitch and longitudinal modes respectively. For the pitch modes, mode shape correlation is reasonable, but the frequencies differ by 22 and 14% between the two results. For the longitudinal modes, the mode shape plot agreement shows dramatic differences and the frequencies differ between 23 and 11 percent. Investigations [3] revealed that differences between the results directly trace to the modeling of joint flexibility that was used to design the scale model, and was not completely understood until the static testing was completed. Had the static test results been incorporated into the design of the scale model, the agreement would have improved. These experiences with the Saturn V program underpin the importance of incorporating component testing, especially the local joint influence coefficient (i.e., force and deflection data), as part of the building block test program. While in this example the model of interest was a physical 1/10 scale model (rather than a FE model in most modern cases), the lessons learned are generally applicable.

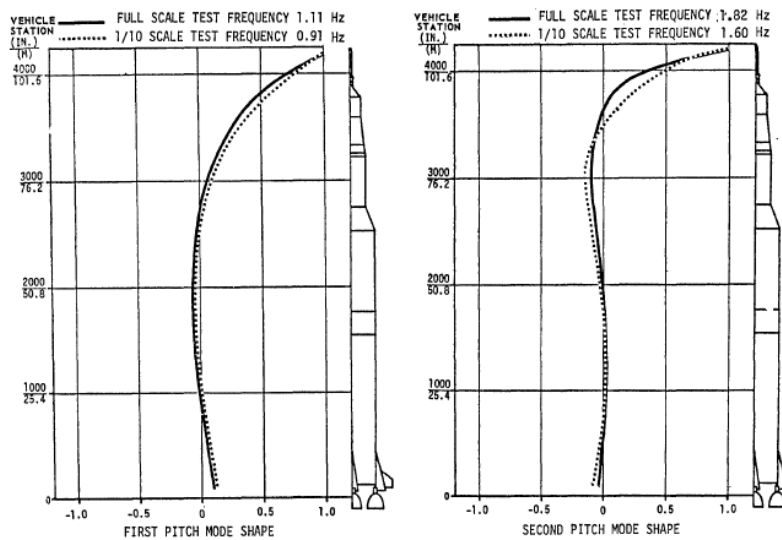


Figure 2. First and Second Pitch Mode Shape and Frequency Comparison between Saturn V 1/10th Scale and Full Scale Tests at 100% Propellant Fill Levels [3]

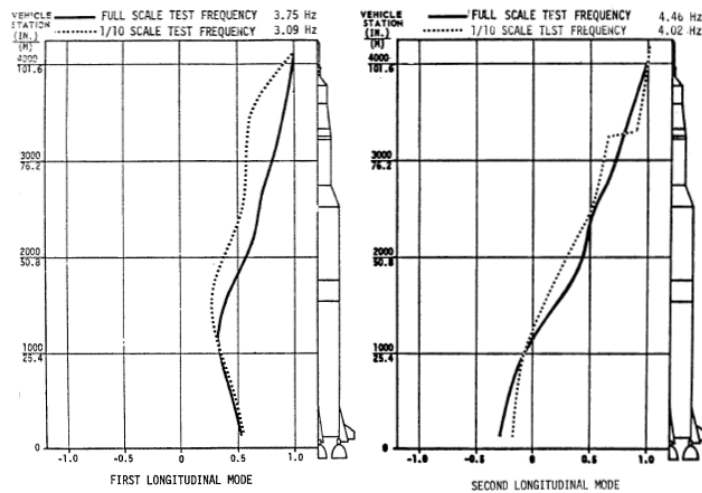


Figure 3. First and Second Longitudinal Mode Shape and Frequency Comparison between Saturn V 1/10th Scale and Full Scale Tests at 100% Propellant Fill Levels [3]

The ground test campaign used for the Saturn V program could not simulate the actual flight conditions for several reasons: some flight hardware had been replaced with mass simulators, a suspension system was not available that could adequately simulate the free-free flight conditions, vehicle cryogenic propellants could not be used, and the flight vehicle configuration for each element was different. Given the maturity of analytical tools at the time that the Saturn V program test campaign took place, initial math models were simple beam rod types and served as the pre-test model in determining test requirements. The primary purpose of the beam model was to understand the sensitivities of replacing LOX with water. The modeling evolved when quarter shell models were developed taking advantage of launch vehicle symmetry while still operating within the computer limitations at the time. These quarter shell models were specifically focused on local modeling of sensor locations and the engine/thrust structure area to understand the sensor slopes. The quarter shell model eventually evolved into a full quarter shell representation of the vehicle. This version of the model proved adequate in predicting bending modes to within four percent. The quarter shell model was unable to predict the sensor slopes nor was it able to predict the coupling between the pitch, yaw, and longitudinal planes due to spacecraft eccentricities. Hence, a three dimensional model was developed to capture these missing effects. The three dimensional model was further simplified in insensitive areas and became the model of record for pogo, loads, and flight control predictions. The three dimensional model consisted of 12,000 stiffness DOF that were reduced to 300 dynamic DOF. Figure 4 shows the evolution of the Saturn V math models including the number of degrees of freedom for each model.

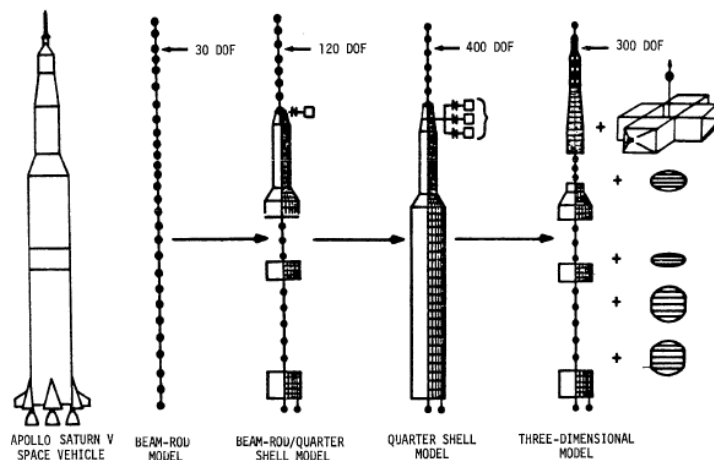


Figure 4. Saturn V System Model Evolution [3]

The Saturn V full scale vehicle testing conducted at the NASA/Marshall Space Flight Center (MSFC) used a 132-channel data acquisition system and a suspension system designed to simulate free-free boundary conditions. The test article was predominantly flight hardware weighing approximately six million pounds. The measured mode shapes are compared with the shapes from the math model in Figures 5 and 6 for the two pitch modes and two longitudinal modes respectively. From the figures, one observes that the frequencies are within four percent for the first four vehicle modes and there is relatively good agreement between mode shapes. What is noted in the literature [3, 4] is that local deformations and major element effects could not be captured in this test. Only through element and localized testing and correlation of math models can these effects be captured and incorporated with any accuracy. This is a key component in any building block approach and re-emphasizes the importance of technical due diligence in all element/component testing leading up to an integrated system test.

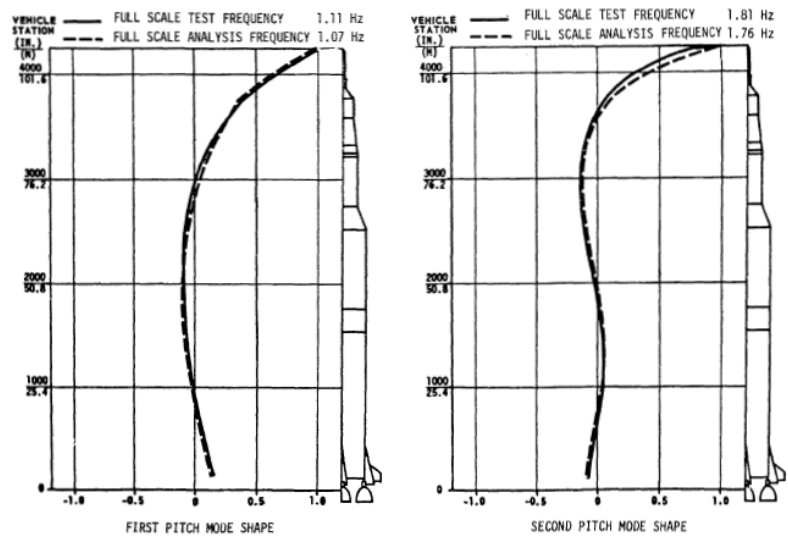


Figure 5. First and Second Pitch Mode Shape and Frequency Comparison between Saturn V System Test and Analysis at 100% Propellant Fill Levels [3]

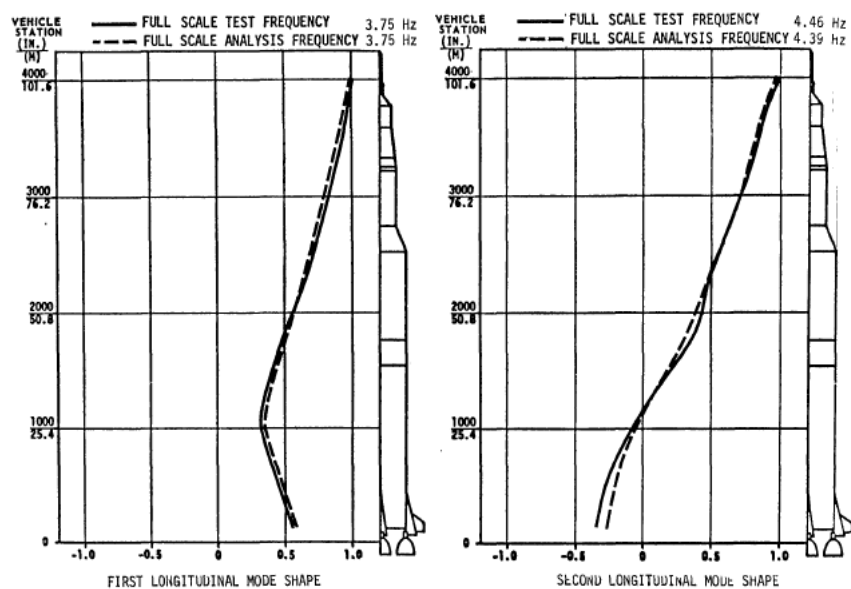


Figure 6. First and Second Longitudinal Mode Shape and Frequency Comparison between Saturn V System Test and Analysis at 100% Propellant Fill Levels [3]

STS EXPERIENCE (1970'S)

The Space Shuttle is the second most notable human space flight program to use a structural dynamic building block approach to validate the system characteristics. There are unique challenges with the Space Shuttle that went outside the experience base of the Saturn V effort, as the Shuttle is a reusable spacecraft. However, there are similarities in overall approaches between the Saturn V and Space Shuttle programs. The shuttle program embarked on a building block approach which sought to test major elements separately and then as a system. There were many discussions on how to approach testing of this new system. In the end it was determined that there was no single test that would answer all stakeholders' requirements. Instead, a systems approach was used to evaluate different stakeholder's requirements and arrive at a set of tests that would provide the necessary validation. These tests comprised the following:

- 1/8th scale model testing – used to understand modeling techniques
- Liquid Oxygen (LOX) tank modal test – used to inform the model of hydrodynamic effects
- Orbiter Horizontal Ground Vibration Test – Used to understand the Orbiter characteristics
- Quarter scale testing – used as early data to inform modeling and to supplement later tests
- Mated Vertical Ground Vibration Test (MVGVT) – used to inform the system model and interface dynamics between elements

There were several other program tests that occurred in the lifetime of the development program that provided opportunities to collect additional experimental data that informed the modeling. These included:

- Main Propulsion Test (MPT) – used to inform the models on engine thrust, frame coupling, and provided pogo transfer functions
- Solid Rocket Motor (SRM) firings – used to inform models about nozzle and actuator dynamics.
- Single Engine Development firings – provided pogo transfer functions and engine gains

Figure 7 below provides an overall view of how these tests were used to satisfy technical requirements.

<u>REQUIREMENTS</u>	<u>STATIC AND COUPON</u>	<u>HGVT</u>	<u>QUARTER SCALE ELEMENT</u>	<u>QUARTER SCALE COUPLED</u>	<u>SSME MPT</u>	<u>LOX MODAL</u>	<u>MVGVT</u>
HYDROELASTIC			S			P	
VISCOELASTIC	P		S				
DAMPING							P
LOCAL EFFECTS/ UNKNOWN							P
LOAD PATHS (JOINTS AND INTERFACES)	S			S			P
UNSYMMETRICAL DYNAMIC COUPLING				S			P
ACTUATOR/ENGINE/THRUST FRAME/LINE COUPLING					P		
SRB ELEMENT MODEL			P				S
SRB PRESSURE EFFECT	P		S	S			
ET MODEL			S			P	S
ORBITER MODE		P	S				S
EXTRPOLATION TO FLIGHT			S	S			P

NOTE: P = PRIME SOURCE; S = SECONDARY SOURCE

Figure 7. Overall Utilization of Building Block Approach for Model Validation of the Shuttle [5]

Of equal importance, the program established, within the overarching verification and validation plan, responsibility and accountability for the element contractors to provide correlated/validated structural dynamic models. Within this same framework, the system contractor had responsibility for providing requirements to the element contractors to enable the assembly of the system model for use in system level GVT activities. The specificity of this approach represents an

evolution from the Saturn V building block approach, and ensured that lower level testing and model validation would infuse test-based information upwardly to the system level.

The complexity of the Space Shuttle provided new challenges that included higher modal density and lower system frequencies approaching 2 Hz. There were new challenges with modeling as the structural dynamic models derived from stress models had approximately 50,000 DOF for the Space Shuttle structure alone. This represents a two-order of magnitude increase in modeling complexity from the Saturn V models.

To touch upon the validation challenges, early testing was carried out with 1/8th scale models and 1/4 scale models followed by component tests, element tests, and systems tests, as outlined in Figure 8. The 1/8th scale model represented a beginning in trying to understand the structural characteristics of the Space Shuttle four body representation (i.e., two boosters, external tank, and Orbiter). This endeavor, while coarse in its representation, confirmed information on low frequency system structural modes (i.e., 200 structural modes below 20 Hz) as well as the coupled interface stiffness that influences these modes.

The 1/8-scale Shuttle Orbiter model program determined the adequacy of analytical modeling technology available at the time (i.e., circa 1974) and was used as in a design of experiments. At the inception, the 1/8-scale mode required that all components (Orbiter, ET and two SRB's) be coupled to determine mated vehicle modes. The technology at the time allowed for a successful calculation of modes for the components, but did not allow for coupling of the structures to form the overall system. The limiting factor was the computing capacity and time available at this period of development. The Orbiter modeling parameters for this effort are show in Table 1.

An initial model, Model I, provided the first basis of comparison between analytical and test modes. The results comparison proved to be less than favorable and exacerbated by the computing limitations. This result in itself focused attention to the modeling, design, and fabrication and improvements were made to the modeling to bring the model and test data into better agreement. Further static and dynamic testing led to further model modifications to improve poor joint modeling and incorporate flexibilities for the fin/fuselage support, forward/mid-fuselage splice, cargo door attachments, wing carry-through structure, payload attachment, and the effective width of the fuselage and wing skins. One of the major takeaways from this effort was that for some joints only static tests could provide the relevant data to model the joint and there was no amount of analytical analysis that could properly characterize these joints. The 1/8th scale model program further uncovered deficiencies in hydroelastic (tank) analysis, which were remedied with details found in NASA Contractor Report-2662 [6]. While these methodologies eliminated fundamental flaws in hydroelastic methodology and modeling, fluid models are not any more reliable than structural models. Therefore, fluid tanks and modeling require the same level of test verification and validation as the structural articles.

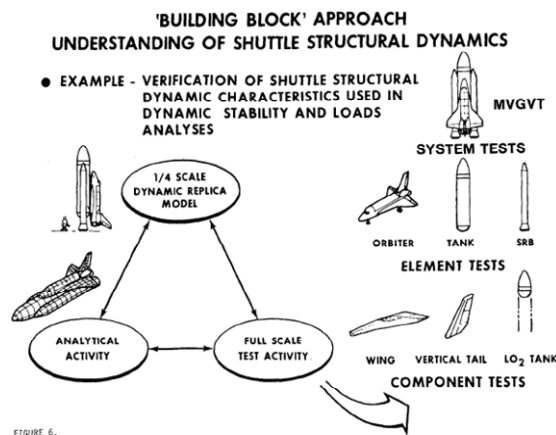


Figure 8. Space Shuttle Program Building Block Approach to Characterizing Structural Dynamics [5]

Table 1. 1/8-scale Test Analysis Model Sizes [7]

Substructure	No. Grid Points	No. CBAR	No. CODMEM2	No. CSHEAR	No. CROD	No. CTRMEM	No. CQUAD2	Total No. of Members	SYMM CASE		ANTISYMM CASE		
									DOF After SPC & MPC	DOF After GUYAN	DOF After SPC & MPC	DOF After GUYAN	
Payload	12	8	—	—	—	—	—	8	24	24	26	26	
Fin	59	—	24	22	65	—	—	111	101	25	99	24	
Wing	192	—	149	81	187	8	—	425	531	183	531	183	
Doors	134	9	20	64	178	—	16	287	396	26	384	26	
Fuselage	537	93	336	172	616	7	—	1224	1417	246	1368	222	
Total ½ Orbiter	934	110	529	339	1046	15	16	2055	2469	504	2408	481	
Orbiter Analysis ST-3	215	Contains 125 plotel elements								400	339	378	324

Table 2 shows a comparison between the Model II (i.e., the updated analytical model with incorporated flexibilities) natural frequencies in Hz and those from scale test data in Hz as well as the March 1973 Shuttle prototype analyses.

Table 2. 1/8th scale Model II Test Data Comparison to 1/8 Scale and 1973 Prototype Model Analysis [7]

1/8 Scale* Model II	1/8 Scale* Test	Prototype**	Normal Mode Description
5.5	5.45	3.56	Fuselage 1st Bending
6.8	6.40	5.26	Wing 1st Bending
—	12.0	5.38	Payload Pitch
—	—	7.23	Payload 1st Bending
15.2	13.4	8.28	Fuselage 2nd Bending
7.9	7.26	11.97	Payload Fore-Aft
—	—	12.32	Aft Crew Comp. Trunion
14.5	13.0	12.59	Wing 1st Torsion
—	—	14.17	Fwd Crew Comp. Trunion
10.0	10.0	14.70	Fin Fore-Aft
—	—	15.40	Wing 2nd Bending
—	—	16.68	Fuselage 1st Longitudinal
—	—	18.00	Fuselage 3rd Bending
—	—	23.05	Fuselage 2nd longitudinal
—	—	24.62	Payload 2nd Longitudinal
*Scale factor on frequencies for replica models if $f_m/f_p = 8/1$ ** Results from Grumman analysis of prototype shuttle current in March 1973 ST-7			

With this information, the program baselined three separate ground vibration tests (GVTs): 1) ¼ scale model GVT; 2) the mated vertical ground vibration test (MVGVT); and 3) a horizontal ground vibration test (HGVT).

The ¼ scale test program set forth to demonstrate that scaled math models could be verified as separate elements and as a coupled system building on the lessons learned from the 1/8th scale model testing and mathematical coupling techniques. The testing further set forth to determine transfer functions between the guidance sensors for the Liftoff configuration (i.e., coupled Orbiter, External Tank (ET), and SRB) and boost configuration (i.e., Orbiter and ET). Further notable modeling challenges that surfaced from the ¼ scale GVT campaign included external tank hydroelastic modeling, solid rocket booster propellant viscoelastic modeling, and modeling of joints between the elements, and modeling tank pressures and its effects on structural modes. Reference [6] provides an overarching summary along with detailed references on testing configurations and analyses addressing the modeling issues that surfaced in the ¼ scale GVT campaign. Once these modeling challenges were addressed, with the exception of the SRB propellant viscoelastic modeling, the following frequency comparisons were achieved for the free-free orbiter and the free-free liftoff configurations. Table 3 provides an example of the ¼ scale results for the coupled Liftoff configuration. Note that the frequency comparisons vary in percentage difference and that the SRB Roll mode shows considerable variability in the test data and when compared to the analysis representation.

Table 3. ¼-scale Liftoff Configuration Test Result Comparison to Analysis [6]

Mode Sequence No.	Test Mode No.	Frequency (Hz)	Analysis Frequency (Hz)	Test Mode Description (Dominant Motion)	Damping Value (C/Cc)
1	44	6.71	8.04	SRB Roll (0.38) and Pitch (0.18) (Repeat of Test Mode 13 at 225 lb Force)	0.044
2	45	7.00	8.04	SRB Roll (0.33) (Repeat of Test Mode 13 at 143 lb Force)	0.032
3	13	7.29	8.04	SRB Roll (0.33) and Pitch (0.18) 63 lb Force	0.036
4	12	10.46	10.22	SRB Yaw (0.95)	0.008
5	4	11.06	12.54	SRB Pitch (0.51) and Roll (0.13) two Shakers per SRB	0.04
6	43	11.12	12.54	SRB Pitch (0.49) and Roll (0.12) one Shaker Per SRB	0.028
7	6	11.71	12.42	ORB Pitch (0.62), SRB Roll (0.13) and Yaw (0.13)	0.015
8	23	12.70	N/A	First Feed Line Fluid	0.013
9	8	15.77	17.39	SRB Axial (0.45) and Yaw (0.35), and ET Lox (M=2, N=2)	0.008
10	9	20.84	26.41 22.76	ORB Axial (0.24) SRB First Z Bending (0.29) SSMEs Pitch (0.21)	0.018
11	1	22.72	22.76	SRB First Z Bending (0.40), Eng's by (0.17) and ET 1 Z (0.15)	0.018
12	2	25.63	27.8	ORB Wing Z Bending (0.90)	0.015
13	14	26.92	30.84	Vert. Tail Pitch (0.40) and Eng. No. 3 Pitch (0.33)	0.017/ 0.027
14	16	27.48	32.36	SRB First Y Bending (0.95) and Wing Z	0.007
15	11	29.68	34.83 35.71	ORB Pitch (0.41), Wind Bending (0.12), and SRB Yaw	0.008
16	10	32.23	31.75	ET Lox (M=1, N=5), (0.77)	0.005
17	21	32.23	32.19	ET LH ₂ Shell (0.12), Lox Shell (0.10), Dome Axial (0.10), Body Flap (0.18)	0.016
18	26	34.08		Body Flat (0.35), Dome Out-of-Phase w/Lox Line	0.010

From the ¼ scale testing came the evolution of both the Horizontal and Mated Vertical Ground Vibration Tests. For the purposes of brevity, we will take an overview of the MVGVT only. Within the program at the integration level, a MVGVT requirements board was formed to facilitate coordination between all stakeholder requirements and ensuring verification objectives are met. To this end, the MVGVT focused on the Liftoff and Boost phases of flight. Requirements from the primary stakeholders are shown in Table 4. These requirements express the necessary accuracy for capturing key experimental parameters to be used in model validation. The objectives for this test were similar to those identified for the ¼ scale test, with the addition of a requirement to measure the response on the external tank feedline to provide data for validating the feedline math model.

Table 4. Key MVGVT Stakeholder Parameters [5,

Items/Users	Control	Pogo	Flutter	Loads
Structure Model	Motion Sensor Gimbal Force	Propellant Pressure Thrust Force	Surface Motion Aero Forces	High Stress Points All Forces
Frequency Range	0 - 10 Hz	0 - 40 Hz	0 - 40 Hz	0 - 40 Hz
Frequency Accuracy	5% < 4 Hz, 10% > 4 Hz	5% < 3 Hz, 15% > 3 Hz	5%	10%
Damping Range	> 0.005	~ 0.01	~ 0.01	~ 0.01
Damping Accuracy	10% < 4 Hz, 20% > 4 Hz	20%	20%	20%
Slope Accuracy	10% < 4 Hz, 20% > 4 Hz	N/A	15%	20%
Deflection Accuracy	10% < 4 Hz, 20% > 4 Hz	20%	15%	20%
Pressure Accuracy	N/A	30%	Not Tested	Not Tested

8]

Details of the MVGVT are captured in Reference [8] with a sample Liftoff system mode shape shown in Figure 9 and a summary comparison between test data and analysis results shown in Table 5.

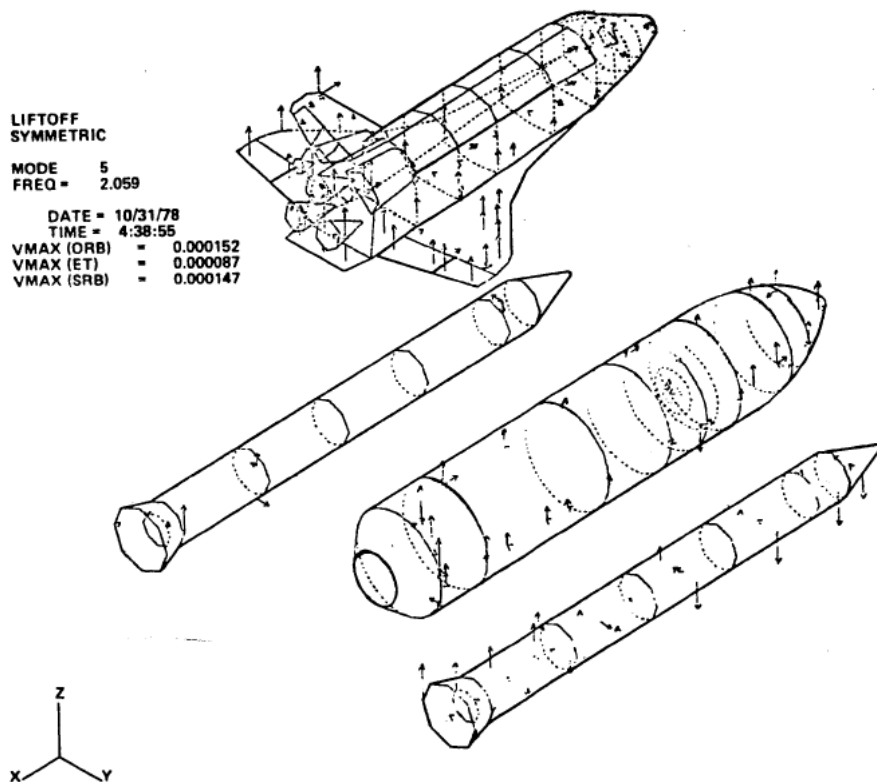


Figure 9. MVGVT Liftoff Mode Shape [5, 8]

Table 5. MVGVT Liftoff Comparison between Test Data and Analytical Results [5, 8]

Test Mode				Analysis Mode			
Mode No.	Freq.	Damp	Description	Mode	Freq.	Description	Percent Error
5	2.05	.013	SRB Roll (.34), Pitch (.25), Yaw (.16), Orbiter Pitch (.08), ET-Z (.13)	4	2.11	SRB Roll (.38), Pitch (.45), Yaw (.04), Orbiter Pitch (.04), ET-Z (.07)	3
7	2.64	.014	SRB Yaw (.95), ET Pitch (.02)	6	2.93	SRB Yaw (.84), ET Pitch (.02)	11
9	3.02	.017	SRB Pitch (.38), Roll (.27), ET-Z, Bending (.10), Orbiter-Z (.07)	5	2.45	SRB Yaw (.83), ET Z (.07)	8
11	3.24	.010	ORB Bending (.33), X (.36), SRB Z-Bending (.25)	8	3.18	SRB Pitch (.38), Roll (.34), ET-Z, Bending (.06), Orbiter-Z (.08)	5
12	3.88	.015	SRB-X (.60), Yaw (.13), Fwd ET Shell (.24)	7	3.14	Orbiter Bending (.44), X (.43), SRB Z-Bending (.06)	-3
23	4.39	.0013	SRB Z-Bending (.22), Roll (.08), F.I. Fluid (.17), Orbiter Bending (.17)	9	3.87	SRB-X (.47), Yaw (.38), Fwd ET Shell (.14)	1
14	5.26	.016	SRB Z-Bending (.47), ET Bending (.27), Orbiter Bending (.17)	11	5.16	SRB Z-Bending (.26), Roll (.06), Orbiter Bending (.54)	18 ^u
15	5.65	.005	Orbiter Pitch, Bending, In-Phase Wing Bending (.55), Orbiter X (.18)	12	5.39	SRB Z-Bending (.15), Y-Bending (.13), ET Bending, Axial (.33), ORB Bend (.15)	2
10	6.43	.037	1st Wing Bending (.68), Out-of-Phase Upper SSME (.13)	11	5.16	Orbiter Z, Bending, In-Phase Wing Bending (.54), Orbiter X (.03)	-9
21	6.78	.011	SRB Sym Yaw and Y Bending (.85)	15	6.69	1st Wing Bending (.64)	3
15	7.92	.011	Vert Tail Fwd Aft Rocking (.21), Out-of-Phase Wing Bending (.18)	18	7.62	SRB Sym Yaw and Y-Bending (.67), Propellant (.12)	12
32	7.45	.031	SSME No. 3 Pitch (.20), Out-of-Phase V.T., Fwd/Aft Rocking (.11)	16	6.88	Vert Tail Fwd Aft Rocking (.07), Out-of-Phase Wing Bending (.22)	-2
27	7.77	.009	1st Lox Tank Bulge, Up LH ₂ (.34), Lox Ogive (.14)	20	8.08	1st SSME Pitch (.50), Out-of-Phase V.T., Fwd/Aft Rocking (.41)	8
16	8.42	.016	SRB 2nd Z-Bending (.62), Roll (.05)	18	7.62	Bulge Mode Overwhelmed by SRB Energy	-2
13	9.00	.008	Orbiter Pitch and Bending (.76), Out-of-Phase SRB Pitch (.06)	22	8.36	SRB 2nd Z-Bending (.67), Roll (.08)	-1
				26	9.40	Orbiter Pitch and Bending (.76), Out-of-Phase SRB (.02)	4

From Table 5, the frequency difference varies from 1 to 18 percent. From the testing, several noteworthy items came to light. Most notably, the left and right SRB forward mounted rate gyros exhibited abnormally high transfer functions, which required a structural redesign. Additionally, it was found that the model for the axial mode of the Space Shuttle Main Engine (SSME) did not correlate well with test due to the simplified modeling technique used. As a result, a three-dimensional, asymmetric math model of the Space Shuttle Main Engine (SSME) and thrust structure was constructed. The pre-test analysis used a symmetric half shell technique to model the structure. Finally, local deformations on the Orbiter bulkhead led to unexpected yaw gyro rates leading to re-modeling of that local area.

While volumes of information exist on the topic, this section has attempted to summarize the procedure used for the Space Shuttle program, to provide a sampling of results showing the degree of correlation obtained in test and modeling, and to highlight lessons learned. The exercises revealed a variety of deficiencies in the analysis models, some of which required redesigning the structure to assure its integrity. Modeling deficiencies occur in unexpected places, often due to joints between components or over-simplification of some components in the analysis model; these would not be captured without a test that identifies a mode that is sensitive to the defect.

EXPERIENCE TO DATE AND PLANS FOR THE INTEGRATED SPACE LAUNCH SYSTEM (SLS)

The HEOMD Explorations Systems Development (ESD) enterprise is comprised of three major programs: Exploration Ground System (EGS), the SLS, and the MPCV. All three programs are separate entities with their own internal governance model. Each program represents a complex system comprised of multiple elements and subsystems. The approach to structural model validation parallels the paths of previous NASA manned space programs (i.e., Saturn V and the Space Shuttle program). Each ESD program has employed a building block approach to utilize component, element, and system testing to validate dynamic and structural models. At the overall ESD integrated system, the system models are integrated for different aspects of integrated operations ranging from rollout from the Vertical Assembly Building (VAB) to the pad, to Liftoff, to Ascent, to landing and recovery operations. Each of these operational phases have a very complex set of interactions that must be understood and modeled within the accuracy of today's current computational methods and abilities. Given the complexity of this system of systems, there is not one test nor one model that can address the physics and complex interactions of these systems. For this reason, the building block approach for this undertaking provides a departure from the previous programs. An example of this departure is there is no scale dynamic modal or static testing of the complete integrated system in the liftoff and boost configuration. The other advantage and rationale for not following the previous

program testing scripts is that there has been large technology advances in computational mechanics and codes. Computer limitations (i.e., solver time, degree of freedom size limits, etc.) are no longer the constraining factor rather the complexity of these new integrated systems and the ability to physically accommodate and test these systems have become one of the limiting factors. Some of the issues revealed in previous programs, such as hydro-elastic modeling and visco-elastic propellant modeling, have become well understood and characterized. The overall test program does leverage accountability and responsibility for product delivery from the Shuttle Program in that the element providers (i.e., contractors) provide the test validated models and the integrated testing system and modeling is the responsibility of the programs.

Full-scale testing is being largely replaced with focus on testing each element in an attempt to validate these models for multiple phases of flight and to within acceptable test and analysis metrics set forth in program requirements. These validated element models become the “true” building blocks for system level modeling. From the element tests, residual modeling uncertainty is captured and an attempt is made to quantify it at the integrated system level in a cumulative manner. This cumulative residual modeling uncertainty is then to be further quantified in an integrated stacked launch vehicle set of tests that will occur prior to the first flight. These integrated stacked launch vehicle system tests in themselves represent a form of integrated ground vibration tests, but do have some potentially important differences when compared to the Saturn V and Space Shuttle ground vibration test campaigns.

The SLS is a heavy lift system that has a capability above the current United States lift capacity to support an efficient and affordable means to meet multiple launch missions in support of human exploration beyond Low Earth Orbit (LEO), and assembly of large and complex structures in space. The SLS includes the following major elements: Stages (Core Stage (includes the LOX, liquid hydrogen (LH2), intertank, forward skirt, and engine section) and Upper Stage), Liquid Engines (Core Stage and Upper Stage), and Boosters (solid). Figure 10 shows an exploded view of the SLS system while Figure 11 shows a representation of the SLS analysis model. The model consists of over 165,000 nodes and over 176,000 elements.

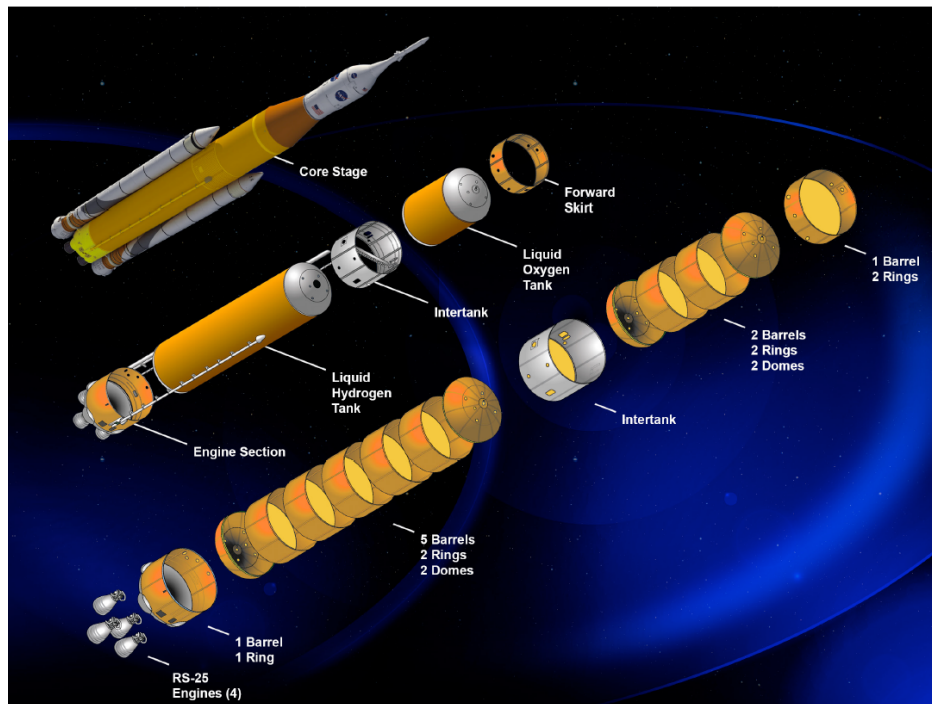


Figure 10. Exploded View of the SLS System

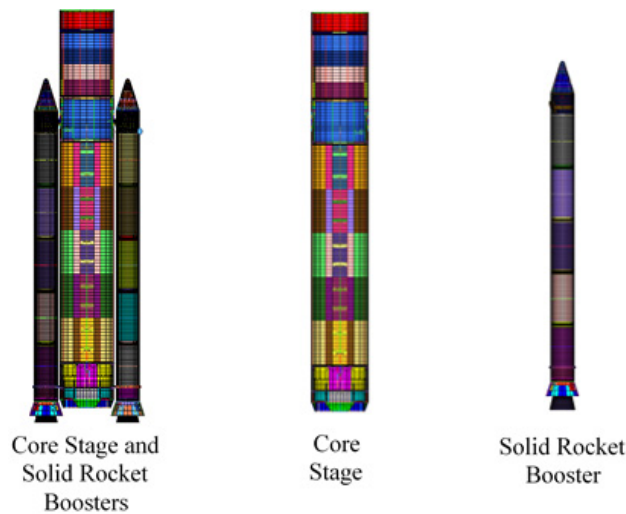


Figure 11. SLS Analysis Model

The Orion MPCV is designed to accommodate flight crews, cargo, and support equipment during Liftoff from Earth to low Earth orbit (LEO) or lunar orbit and subsequently return the crew to Earth. The Orion MPCV, Figure 12, is comprised of three modules: the Launch abort system (LAS), the crew module (CM), and the European service module (ESM).

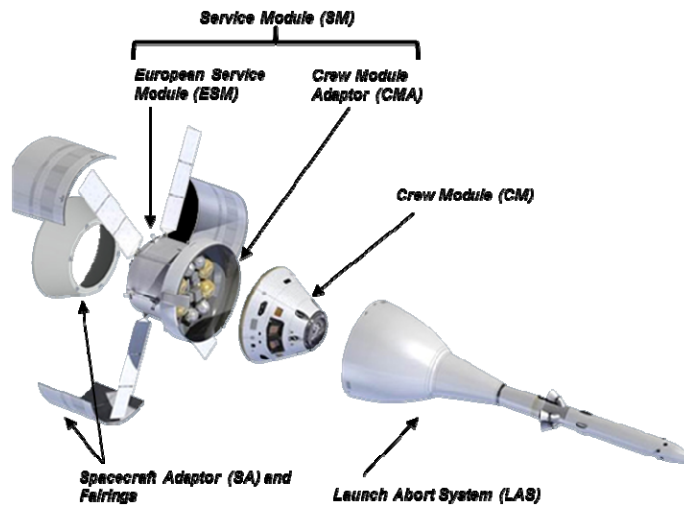


Figure 12. Exploded View of the Orion MPCV System

The LAS tower, positioned atop the crew module, activates within milliseconds to propel the crew module to safety in the event of an emergency during Liftoff or climb to orbit. The system also protects the crew module from dangerous atmospheric loads and heating during the initial mission phase of ascent to orbit and is subsequently jettisoned. The crew module is the transportation capsule that provides a safe habitat for the crew, provides storage for consumables and research instruments, and serves as the docking port for crew transfers. The crew module is the only part of the MPCV that returns to Earth after each mission. The ESM supports the crew module from Liftoff through separation prior to reentry. It provides in-space propulsion capability for orbital transfer, attitude control, and high-altitude ascent aborts. When mated with the crew module, it provides the water, oxygen, and nitrogen needed for a habitable environment, generates and stores electrical power while on-orbit, and maintains the temperature of the vehicle's systems and components. The analysis model representation of the integrated Orion MPCV is shown in Figure 13. The model consists of over 1.3 million nodes and over 1.5 million elements.

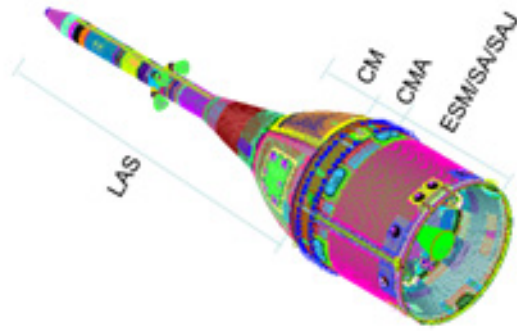


Figure 13. Integrated Orion MPCV Analytical Model

The SLS family of vehicles will be stacked, rolled out, and launched from the Mobile Launcher (ML). The ML consists of an Ares I derived tower structure and a Space Shuttle derived base structure. The ML tower, measuring 4152 inches tall, 1329 inches wide, and 718 inches deep at its base, will supply power, propellant, personnel access, and lateral support to the vehicle. The ML base, measuring 291 inches tall, 1596 inches wide, and 1896 inches deep, is the platform on which the vehicle is vertically supported during its assembly, rollout, and prelaunch. There are eight vehicle support posts (VSPs) on the ML base that constrain the vehicle to the pad; four VSPs constrain the aft skirt of the left-hand booster and four VSPs constrain the aft skirt of the right-hand booster. Figure 14 provides an integrated model of the SLS stacked system sitting atop the ML.

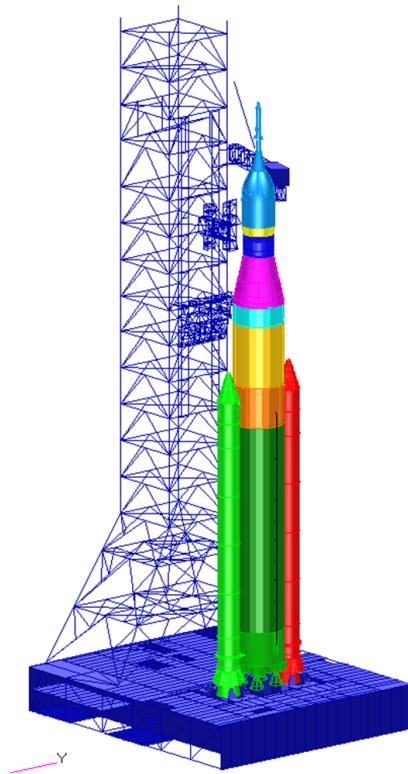


Figure 14. Analytical Model Representation of the Integrated Stacked SLS System on the ML

Improvements in computational methods provide the ability for a more detailed modeling process compared to what was available in the past for Saturn V and the Space Shuttle program. However, more is not necessarily better. Many of the

challenges that existed in the past that still exist today. For instance, the models have lots of detail but still have dramatic simplifications in geometry. This issue manifests itself in two specific areas in particular: 1.) in the interfaces where critical joint simplifications are made and where possible non-linear behavior may exist and 2.) in the modeling of orthogrid and isogrid structures. As a result, the models may be more predictive than the models used historically, but there are still many places where they could be wrong. Furthermore, while these models are larger it has still been necessary to create reduced order models for certain subcomponents (e.g., Hurty/Craig-Bampton). This is done both for practical reasons (to facilitate sharing of models) and to reduce the computational burden. As a result, issues may arise in these models due to this reduction process; it is not always possible to retain enough modal information to span the frequency range of interest, and when simplifying the models in this way there is always the potential for errors and model grounding issues.

Table 6 provides a condensed form of both element and system testing currently in process for the first exploration mission flight. While the information does not include all tests planned and on-going, it provides awareness of the comprehensive program undertaken to address the building blocks of these systems of systems.

Table 6. Building Block Tests for the First Exploration Mission Integrated Stack Vehicle

Test Designator	Test Description	Test Type
Crawler Transporter (CT) /ML/VAB Move Operations to VAB	Rollout without stacked SLS vehicle to VAB	Operational
SRB Modal Survey Test	Full scale modal survey of the five-segment Experimental Solid Rocket Motor 3	Dynamic
FSTA-1, 2	Forward Skirt Static Test Article 1 and 2	Static
LOX Tank SQT	LOX Tank Static Qualification Test (SQT)	Static
LH2 Tank SQT	LH2 Tank Static Qualification Test	Static
LH2 Proof Test	LH2 Proof Test	Static
ES SQT	Engine Section (ES) Tank Static Qualification Test	Static
Intertank SQT	Intertank Tank Static Qualification Test	Static
LOX Forward Dome Tap Test	LOX Forward Dome Tap Test	Dynamic
LOX Aft Dome Tap Test	LOX Aft Dome Tap Test	Dynamic
CS Suspended Modal	Core Stage Cable Suspended Modal Test	Dynamic
LVSA +ICPS+MSA Modal	Launch Vehicle Spacecraft Adapter (LVSA) + ICPS + MPCV Spacecraft Adapter (MSA) Modal Test	Static/Dynamic
E-STA	European Service Module Static Test Article (E-STA)	Static/Dynamic
M-STA	Multi-Purpose Crew Vehicle Static Test Article (M-STA)	Static/Dynamic
Booster Pull Test	Booster Pull Test on ML during stacking operations	Static
PSMT	Partial Stack Modal Test (ML, Boosters, Core Stage)	Dynamic
IMT	Integrated Modal Test (Flight vehicle & ML)	Dynamic
DRT	Dynamic Rollout Test (Flight vehicle & ML on Crawler)	Dynamic

The tests listed in Table 6 once again re-emphasize that the focus in this building block approach is on the element testing and does include both static and dynamic testing to be used in model validation. As mentioned previously, one of the critical focus areas in the modeling are the joints, especially around major interfaces, in particular the way in which they are simplified. This is recognized by the system analysts and discussion early on with element providers focused on providing requirements to gather interface influence coefficient data (i.e., force deflection data) for modeling purposes.

The structural testing and modeling campaign will culminate with system testing that consists of modal tests to be conducted on the flight hardware at the Kennedy Space Center (KSC) prior to the first exploration mission launch. The tests consist of the ML Only test, the booster pull test, partial stack modal test (PSMT), and the integrated modal test (IMT). Each of these tests will have differing boundary conditions to aid in characterization of ground and Liftoff conditions and to aid in understanding the system modes between the three constituent systems (ML, SLS, and Orion MPCV). These modal tests represent the current program's corresponding series in place of a dedicated IVGVT. Figure 15 shows how the element tests map to the system level tests and how each system tests builds on the result of the previous test.

Verification and validation (V&V) is a highly challenging undertaking for SLS integrated stack structural dynamics models due to the magnitude and complexity of SLS subassemblies and subassemblies. There are a number of issues that contribute to the overall challenge. Nearly all modal testing will be conducted on non-fueled assemblies and subassemblies in the 0-60 Hz frequency band. Modes that exercise the fueled structure in this frequency band have non-fueled counterparts at natural frequencies well in excess of 60 Hz. Absence of ersatz LOX (water) in the LOX tank is a departure from the STS modal test program, and it represents a challenge in understanding the tank dynamic effects as the lowest frequency full-tank body modes are of different character than empty tank modes. Addition of a series of LOX tank fill level modal tests would reduce the uncertainty, but current plans are to trust to modeling to account for the fuel.

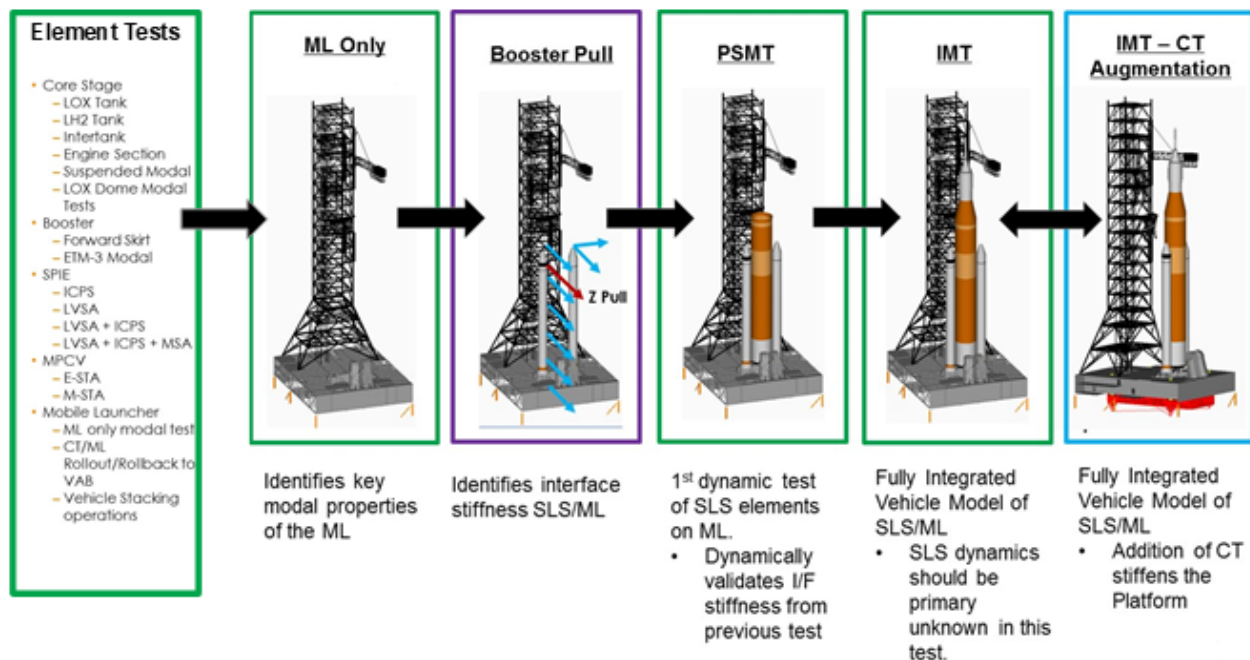


Figure 15. Integrated SLS Stacked System Level Testing

Many SLS and Orion MPCV components are configured as thin, complex construction (waffle, etc...) shell structures with attached, localized structural subassemblies (e.g., ISPE). Overall body, shell breathing, and localized subassembly dynamics in the 0-60 Hz frequency band produce a variety of technical challenges including coupling of body, breathing and local kinetic energies in individual modes due to configuration features and imperfections, sensitivity of shell breathing modes to

static (pressure) loads, and sensitivity of modes to uncertainties primarily in joint stiffnesses. To address some of these issues, a mode consolidation (MC) strategy is available that can consolidate “split” or “fragmented” modes [9]. This uses selected shape functions, defined in a modified Guyan reduction (MGR), to select “body dominant” system modes on the basis of kinetic energy distribution, and consolidate apparently repeated “body dominant” modal fragments into idealized body modes of an apparent “de-featured” dynamic system. By employing MC for the experimental modes combined with MGR for the system mathematical model, test-analysis correlation and reconciliation may be more effective and can deliberately focus on target modes.

There exist a large number of modes (i.e., ~1000s for the entire integrated stacked SLS system) in the 0-60 Hz frequency band, resulting in the following technical challenges; (1) Modal test planning and execution requires large instrumentation and excitation resources to appropriately capture the system modes, (2) practically achievable test-analysis correlation and reconciliation must focus on a target mode subset, which is difficult to properly select, and (3) experimental modal analysis of systems with many closely-spaced modes requires objective quality metrics that are independent of mathematical model predictions.

With regard to the integrated system test (e.g., PSMT, IMT, etc.), the primary challenge is the coupling of the SLS vehicle stack with the ML. The SLS is flight hardware and as such there are detailed drawings, traceable plans and fairly well-developed models. In contrast, the ML is a large steel structure akin to a bridge or building, and its construction is not controlled in the same way; efforts to model it are also less mature yet it has many, many modes in the frequency range of interest for the SLS and so its influence cannot be neglected. Hence, it may prove challenging to model the ML with sufficient fidelity that one can use the coupled SLS+ML test to assess the accuracy of the SLS dynamics model. Decoupling of the SLS vehicle stack from the complete “article” should rely on a low-risk strategy. To address this challenge, an ML Only test is planned to obtain dynamic characteristic data to inform the PSMT. The PSMT test will provide the first set of integrated data to understand fully the degree of coupling between the vehicle and ML. To date, all that is available are analytical simulations using uncorrelated models. The simulations to date do suggest that modes above ~3 Hz becomes highly coupled and hence potentially problematic. The PSMT test then informs the IMT testing moving forward. One method still under investigation and in process of vetting is using the CT to lift up on the ML base while still connected to another set of mounts. Simulations have shown that this may stiffen the ML base and decrease the coupling between the ML and the integrated stacked vehicle dynamics. Further, alternative data extraction methods are being explored to extract fixed base modes of the SLS from the IMT test including the fixed base extraction method developed by Napolitano [10, 11] and the dynamic substructuring method developed by Allen and Mayes [12].

Clearly, the integrated stacked SLS testing campaign draws on the history and lessons from the past manned space flight programs. The building block approach focuses on element testing and seeks to exploit advancement in computational mechanics and modeling techniques, seeking to minimize testing and exploit models to the extent possible while using both static and dynamic data to address unknowns in the models and to check for errors or “unknown-unknowns”. Many challenges still exist as the testing campaigns continue and technical due diligence is required given the limitations imposed on testing due to schedule, hardware, and programmatic constraints.

CONCLUSION

The National Aeronautics and Space Agency (NASA) manned flight programs has an enduring technical history in developing high performance flight systems, and in developing approaches to model, test and validate these complicated vehicles. The approach to understanding these systems is steeped in using a building block approach to understanding the fundamental physics of the integrated structural systems and developing test validated models for use in system analyses. From the Saturn V program to the current integrated stacked SLS system, the general premise of the building block approach was and is employed. The approach has evolved and leveraged lessons learned and observations from the past, while some challenges remain the same.

It is vital to remember that system-level structural dynamic models will be required for computing expected launch and flight loads, and for control and pogo stability analyses. These models will be derived from detailed subsystem FEMs, which will

be provided by various elements/organizations. In addition, there is a need for FEMs to predict internal loads and stresses to establish expected structural margins, and for supplementing and supporting strength testing. These models will be required to deal with manufacturing non-conformances. Because of the size and complexity of today's modern integrated systems, significant testing is required to obtain sufficient data to adjust/correct the various subsystem FEMs that will be used to generate the system-level models.

Unique system-level models will be required for numerous times of flight, including liftoff, post-liftoff, various atmospheric flight times, post SRB jettison, exoatmospheric flight, post Launch Abort System (LAS) jettison, post CS separation, and post second stage separation. As such, it is not possible to perform system level testing for all possible flight configurations and propellant loading levels. This leads to the requirement that test adjusted subsystem FEMs, which can be configured analytically to the various flight configurations, be available to generate the required system models. Hence, it is critical to assure that high quality models are created and that the appropriate testing and model tuning activities are performed to catch errors and mitigate uncertainties.

Based on the above considerations, and the complexities involved in mode survey tests of systems with a large number of modes, it is concluded that a system-level GVT by itself cannot provide the data needed to develop accurate subsystem FEMs, which are required to develop models of the coupled system for the various times in flight where analyses are required. The past manned space flight programs and the current integrated SLS stacked system have developed an approach in which subsystem FEMs are tuned to subsystem mode survey and static test data. In this approach each subsystem element organization is responsible for the quality of the tests and final models delivered for integration into the system models. All of the programs, past and present, have instituted some form of GVT that provides additional valuable data as the vehicle elements are being integrated.

Successful implementation of the building block approach requires that uniform criteria are implemented across the elements to gauge the success of the test and model correlation/correction. This includes adherence to standards and implementation of a structural verification plan that specifies consistent test and model correlation requirements for all the elements. These include mode survey test completeness and mode shape orthogonality criteria, model to test frequency and mode shape comparison criteria, and the requirement that all FEM changes made to improve agreement with test data must be consistent with the drawings and the hardware.

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