

ADVANCES IN NON-DESTRUCTIVE BUCKLING PREDICTION OF THIN-WALLED STRUCTURES BY VIBRATIONS

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Abstract

Buckling remains one of the dominant design criteria for thin-walled launcher structures and other lightweight shell components. The challenge is particularly severe for cylindrical, conical and doubly curved shells, whose load-carrying capacity is strongly affected by manufacturing imperfections, boundary conditions, load introduction and local design details. A destructive compression test provides the most direct evidence of the real buckling load, but such a test is often incompatible with qualification campaigns in which the same hardware has to survive several load cases. The Vibration Correlation Technique (VCT) offers a non-destructive alternative: the load-dependent evolution of natural frequencies is used to extrapolate the buckling load before global instability is reached. This paper consolidates recent developments reported in eight related studies. The central result is the first qualification-scale application of VCT to an Ariane 6 test article, where reliable buckling predictions were obtained for a full-scale launcher barrel under combined axial-bending loading. This industrial validation is complemented by multimodal experimental verification of a payload fairing panel and numerical studies on unstiffened CFRP cylinders and double-curved shells. Particular attention is given to alternative VCT formulations developed for cases in which the standard Arbelo-type characteristic chart may yield non-conservative estimates. The synthesis shows that the standard Arbelo approach remains a robust baseline, while selected modifications may provide additional safety or accuracy for specific imperfection-sensitive cases. The paper concludes by outlining future work on double-curved structures, shells with cut-outs and structures with local degradation, where local buckling phenomena may limit the applicability and predictive capabilities of VCT.

Keywords: VCT; buckling prediction; thin-walled structures; imperfection sensitivity; launcher structures

1. Introduction

Thin-walled shell structures are used wherever stiffness and load-carrying capacity have to be achieved with minimal mass. In launch vehicles this requirement is especially demanding, because tanks, adapters, payload fairings and related cylindrical or conical shell segments are exposed to compression, bending, shear, torsion and combinations of these load components. For such structures, buckling is not a secondary design check but often the limiting failure mode. The problem is amplified by the fact that shell buckling is highly sensitive to small deviations from the nominal geometry. Manufacturing-induced mid-surface imperfections, local thickness variations, boundary-condition imperfections, load eccentricities and local details such as welds, doors, inserts or cut-outs can shift the buckling load far below the value obtained from idealized linear theory.

Classical design guidelines have traditionally addressed this uncertainty through conservative knock-down factors. NASA SP-8007 for cylinders, NASA SP-8019 for cones and NASA SP-8032 for doubly curved shells represent the historical basis for many engineering assessments. These documents established safe lower bounds, but their empirical nature also means that they may prevent efficient use of modern manufacturing quality and advanced numerical modelling. The 2020 revision of NASA SP-8007 strengthened the role of analysis-based approaches, in which validated high-fidelity models and measured imperfections support more realistic design loads. Nevertheless, a distinction has to be made between predicting a design load before manufacturing and verifying the load-carrying capacity of a real test article after it has been produced.

For a manufactured shell, the most direct verification would be to load the structure until buckling. In qualification campaigns this is usually not acceptable. The structure may be needed for subsequent load cases, further dynamic tests, environmental tests or even integration into larger assemblies. A destructive test also provides only one data point and may not be compatible with expensive full-scale launcher hardware. This motivates non-destructive experimental methods capable of estimating the buckling load from the prebuckling range. VCT is one of the most promising approaches in this category. It uses the fact that natural frequencies change under increasing load and, for many structures, tend toward zero at the stability limit.

The present article consolidates the main outcomes of a sequence of studies devoted to extending VCT from small laboratory shells toward realistic launcher structures and broader structural classes. The most important achievement is the reliable application of VCT to the Ariane 6 test article described in [8]. This was the first demonstration that the method can provide useful, non-destructive buckling predictions during a full-scale qualification-relevant test with combined axial-bending loading and multi-actuator load introduction. A second industrially relevant step is the multimodal verification of a composite payload fairing panel described in [7], where load-dependent vibration measurements were used to validate a complex numerical model and to identify modes relevant for future VCT-based prediction.

The consolidation also covers methodological developments intended to increase robustness in difficult cases. For unstiffened CFRP cylinders, several studies showed that the Arbelo characteristic chart is generally reliable, but that particular imperfection maps or normalization choices may lead to non-conservative predictions. The lambda factor approach proposed in [1], the robustness analysis under scaled and inverted imperfection maps [5], and the analytical bifurcation load modifications introduced in [6] are therefore reviewed as complementary ways to handle such cases. Further sections discuss VCT applications to CFRP truncated cones [4] and combined loading [2], followed by a separate discussion of double-curved shells [3], where VCT was not applied directly; instead, the study identified a relevant spectrum of structural cases in which VCT may potentially be used for future buckling-load estimation based on stability analyses with SPLA, MSI and LBMI imperfection concepts. The final part identifies open problems related to local buckling, cut-outs and local material or geometric degradation.

2. Evolution of VCT and characteristic charts

2.1 From the classical frequency-load relation to shell applications

The earliest VCT idea is based on a simple mechanical observation: when a structure under compression approaches its critical state, the stiffness associated with a corresponding vibration mode decreases and the related natural frequency is reduced. For columns, beams and many plate-like structures, the squared frequency can be related approximately linearly to the applied load. In the classical representation, the normalized squared frequency decreases with the normalized applied load, and a linear extrapolation can be used to estimate the load at which the frequency would vanish. This interpretation is physically transparent when the vibration mode and buckling mode are essentially the same.

The apparent simplicity of the classical VCT chart is also the reason for its limited applicability to real imperfection-sensitive cylindrical shells. VCT is applied only within the prebuckling range; therefore, the prediction must be inferred from the frequency response measured before instability occurs. For perfect

cylindrical shells, the squared natural frequency may decrease linearly with the applied compressive load and reach zero at the corresponding critical bifurcation load. In real unstiffened shells, however, the load-carrying capacity is usually reduced by initial imperfections, so buckling occurs at a load lower than the linear critical load of the ideal structure. Consequently, the frequency-load path is interrupted by the actual buckling event before the zero-frequency state is reached. The final part of the classical characteristic relation, which would be required for a direct extrapolation to zero frequency, is therefore not physically accessible in the real experiment. Even when the measured relation between the squared natural frequency and load appears nearly linear within the available prebuckling range, extrapolating this trend to zero frequency would generally lead to a prediction higher than the actual buckling load. This inherent non-conservatism disqualifies the classical chart as a reliable basis for buckling-load prediction in imperfection-sensitive unstiffened cylindrical shells. This limitation motivated the development of modified characteristic charts that preserve the non-destructive character of VCT while accounting for the unstable loss of stability caused by geometric imperfections.

2.2 Souza and Arbelo formulations

A significant step in the development of VCT for shell structures was the semi-analytical approach proposed by Souza for imperfection-sensitive stiffened shells. The method reformulated the characteristic chart by using transformed load and frequency coordinates. This provided a better fit for some stiffened configurations but was not universally suitable for unstiffened cylindrical shells, where the fitted parameter could become non-physical. The subsequent formulation proposed by Arbelo changed the frequency coordinate and introduced a second-order best-fit curve. The prediction is obtained from the minimum of the fitted parabola, which is interpreted through an experimentally estimated load reduction (cf. Fig. 1).

In the Arbelo formulation the essential quantities are the applied load normalized by a reference critical load and the loaded natural frequency normalized by the unloaded natural frequency of the same mode. The quadratic fit is constructed in the characteristic plane and the buckling load is inferred from the minimum of this curve. This approach proved effective for several experimental campaigns on composite and metallic cylindrical shells [9-17]. Its importance lies in the fact that it converts a strongly nonlinear frequency evolution into a practical prediction framework, while retaining a simple experimental procedure based on vibration measurements at several load levels.

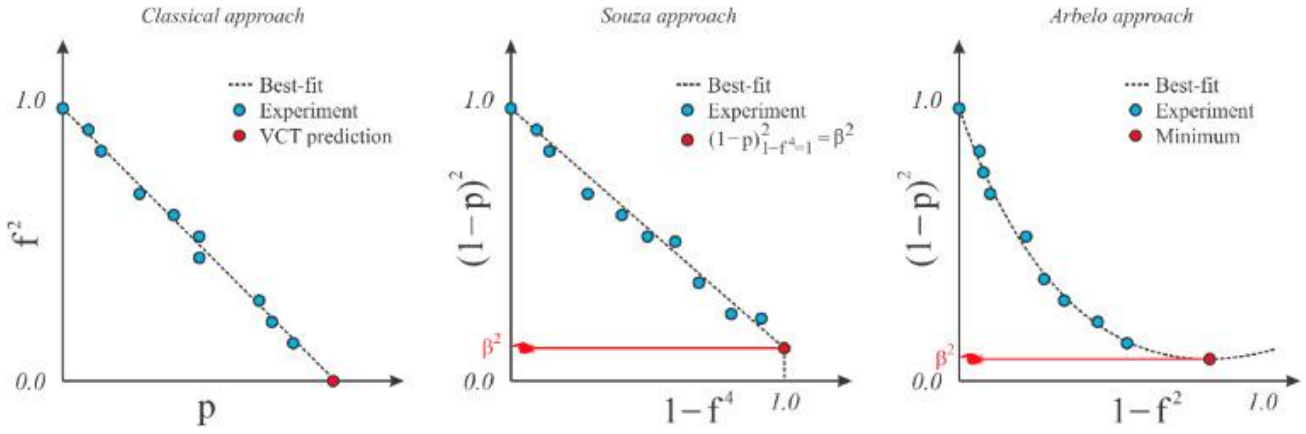


Figure 1 - Evolution of VCT characteristic charts: classical linear chart, Souza-type chart and Arbelo-type chart.

2.3 Analytical support and practical implications

Initially, the Arbelo chart was empirical. Later analytical work [18] strengthened its physical basis for imperfection-sensitive cylindrical shells. This development was crucial because industrial adoption requires more than a curve that works for selected specimens: it requires an explanation of why the chart can represent the prebuckling dynamic response. The analytical verification reported in earlier VCT studies and summarized in [18] helped to place the method on a firmer foundation and encouraged its further extension toward real-scale hardware.

From a practical standpoint, the Arbelo chart introduces two normalization parameters that are easy to define numerically but not always trivial to validate experimentally: the unloaded natural frequency and the reference critical buckling load. The unloaded natural frequency can usually be measured and compared with the FE model. The reference critical load, however, is obtained from an analytical or numerical model and cannot be measured experimentally. This dependence makes VCT partly experimental and partly model-supported for thin-walled shells. Much of the recent work discussed in this paper investigates how sensitive the prediction is to this normalization and how the chart can be modified when the standard definition becomes problematic.

2.4 From downscaled specimens to qualification-scale hardware

Before the Ariane 6 application, VCT had been validated mainly on laboratory-scale cylinders and related shell specimens. These studies demonstrated that, when appropriate modes are tracked and sufficiently high load levels are reached, the method usually provides conservative estimates that improve as the maximum considered load approaches the nonlinear buckling load. However, qualification-scale hardware introduces additional complications. Load introduction is performed through large test rigs, boundary conditions are not ideal, local structural details affect the response, and the test sequence is often dictated by safety and qualification requirements rather than by the needs of VCT. The transition from small specimens to a real launcher test article therefore represents a major step in maturity.

This transition is also important because the full-scale test environment is not a clean modal laboratory. Vibration excitation and measurements have to be performed in the presence of hydraulic actuators, support frames, limited optical access, time constraints, safety limits and possible local instabilities. The successful application described in [8] demonstrates that VCT can still deliver meaningful predictions under such constraints. It also shows why modern VCT should be understood as an integrated procedure combining vibration measurements, mode identification, finite element support, imperfection modelling and engineering judgment concerning mode selection and load-step interpretation.

3. Reliable buckling prediction for the Ariane 6 test article

3.1 Test article and load cases

The most important consolidated result is the application of VCT to the Ariane 6 test article reported in [8]. The investigated structure was a full-scale launcher tank barrel representative of the lower section of the hydrogen tank of the Ariane 6 first stage (cf. Fig. 2). The barrel consisted of four welded aluminium panels and was tested as part of a structural qualification campaign. The campaign was conducted under conditions that are much closer to industrial qualification than to a conventional laboratory VCT experiment. This distinction is essential: VCT was not the sole purpose of the test, but an additional non-destructive evaluation method integrated into an already demanding qualification context.

Two load cases were considered. In the first load case, denoted as LC1, three of the four actuators were active, creating a combined axial-bending state with a more distributed compression pattern. In the second load case, denoted as LC2, two actuators were active while the remaining actuators were mass-compensated, resulting in a different axial-bending distribution and a different sensitivity of the measured response. The goal was not to reproduce a purely axial compression test, but to examine whether the frequency-based buckling prediction can remain meaningful when the load field is representative of realistic qualification scenarios. The test article, actuator layout and region of interest should be introduced early in the article because they define the industrial relevance of the validation.

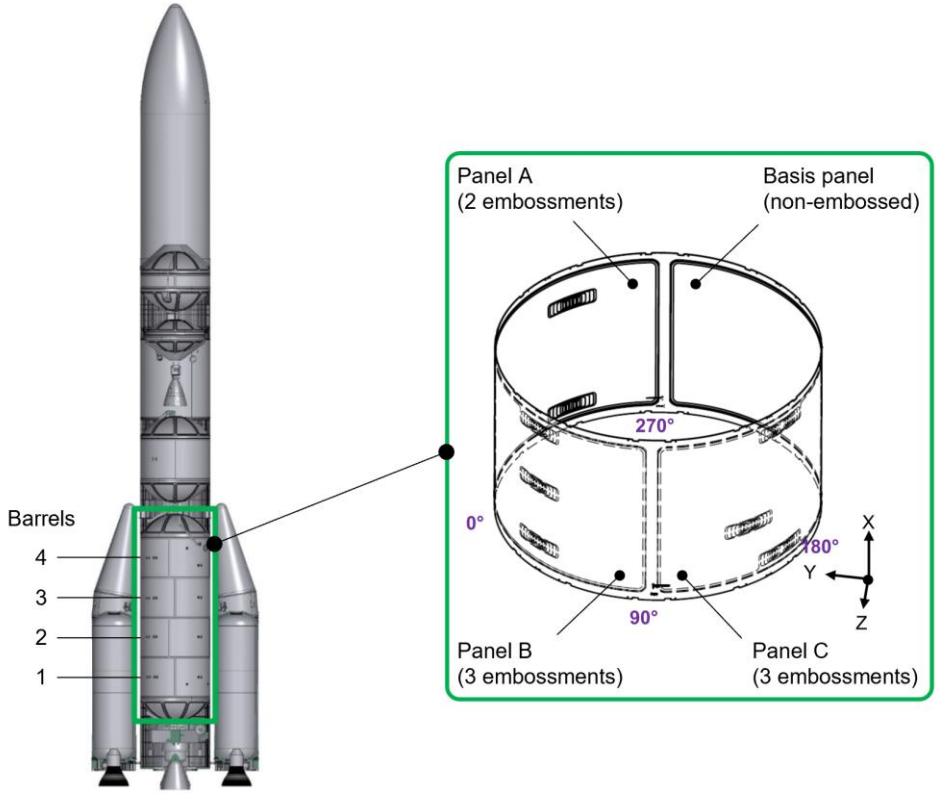


Figure 2 - Ariane 6 LH2 tank barrel, hybrid test article and investigated region used for the VCT campaign.

The experimental buckling load was 485.1 kN in LC1 and 356 kN in LC2. In LC2 the measured buckling load corresponded to about 87% of the FE prediction available for the campaign. These values provide the reference against which VCT predictions were assessed. The study also reported local buckling phenomena before or close to global instability. In LC1, local buckling affected the last VCT steps after a preload event around 80.7% of the experimental buckling load. In LC2, local buckling was detected at approximately 97% of the global buckling load. These events are not secondary details; they directly affect the modal response and illustrate why VCT interpretation for full-scale structures must include careful monitoring of mode changes.

3.2 Measurement system and numerical support

The VCT measurement setup used acoustic excitation and laser vibrometry. A loudspeaker excited the barrel over the frequency range of interest, while a Polytec scanning laser vibrometer measured vibration velocity on a grid located in the region monitored during the test. For LC1, a 10 x 8 grid was used, whereas LC2 used a 7 x 9 grid (cf. Fig. 3). The frequency resolution was improved from 0.125 Hz in the first experiment to 0.1 Hz in the second experiment. This adjustment was important because the first experiment showed that closely spaced low-frequency peaks can limit mode recognition. The setup demonstrates that VCT can be implemented using contactless excitation and measurement techniques, which is particularly valuable for qualification hardware where any physical contact with the test article should be minimized.

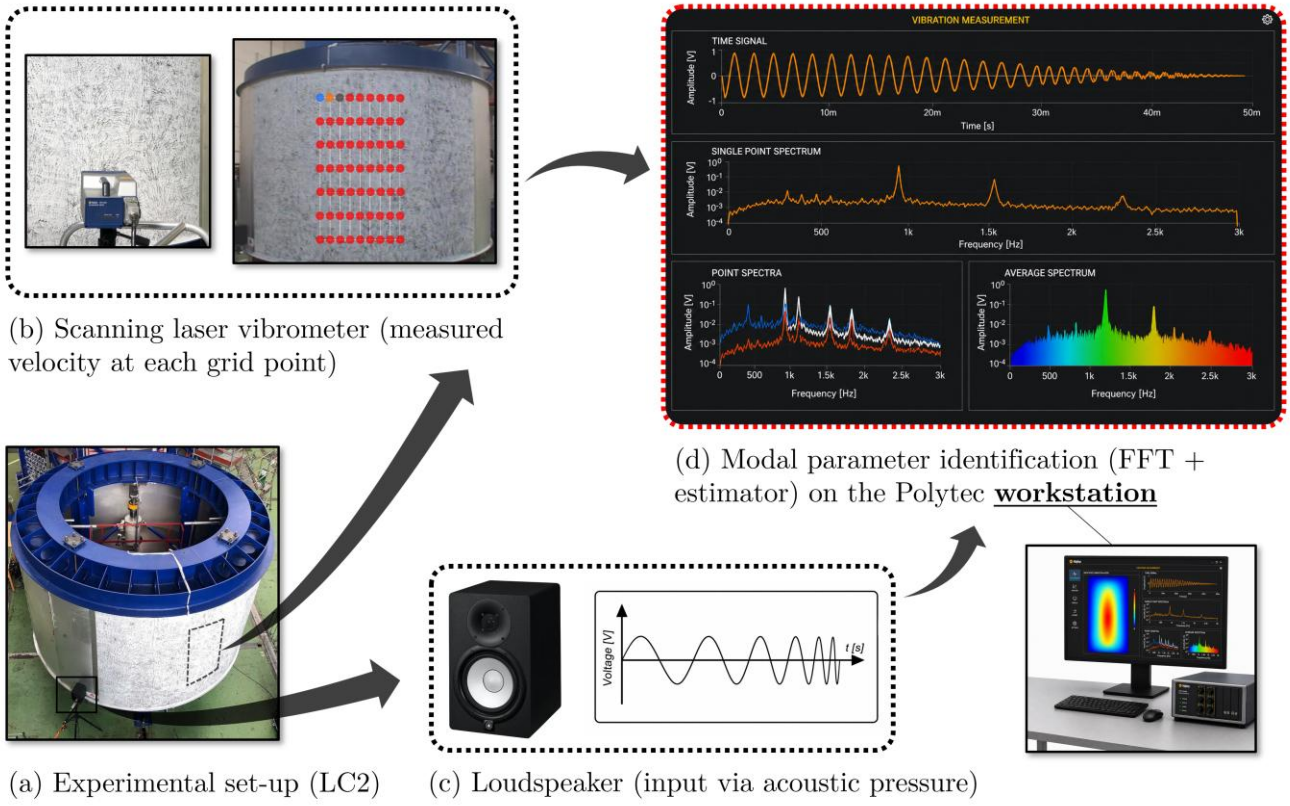


Figure 3 - Ariane 6 VCT experimental setup: laser vibrometer, acoustic excitation and modal identification workflow.

The experimental campaign was supported by detailed FE modelling (cf. Fig. 4). The model included the shell section distribution, support-frame superelements and actuator representations. A stochastic imperfection framework was also introduced, using random Fourier-based fields in addition to classical linear buckling-mode imperfections. This numerical part served two purposes. First, it provided a pre-test reference for expected buckling loads, imperfection sensitivity and relevant vibration modes. Second, it allowed the VCT procedure to be evaluated numerically for representative imperfection patterns before applying it to experimental data. The study showed that linear buckling-mode imperfections provided a conservative baseline, while stochastic Fourier imperfections offered a broader representation of possible imperfection variability when measured geometric maps were unavailable.

The numerical results highlighted the strong imperfection sensitivity of the full-scale barrel. For example, the pristine model produced much higher nonlinear capacities than the imperfect models, while Fourier imperfections applied over the entire structure could generate the lowest capacities for larger amplitudes. In the simulated set, the 20th percentile nonlinear capacities for the primary actuator were 199.74 kN for LC1 and 204.58 kN for LC2. The experimental buckling loads remained below the corresponding percentile-based total-load reference, emphasizing the difficulty of fully capturing all relevant imperfections and local stiffness reductions in large welded structures. This does not weaken the VCT validation; rather, it shows the value of an in-situ method that incorporates the actual structural response into the prediction.

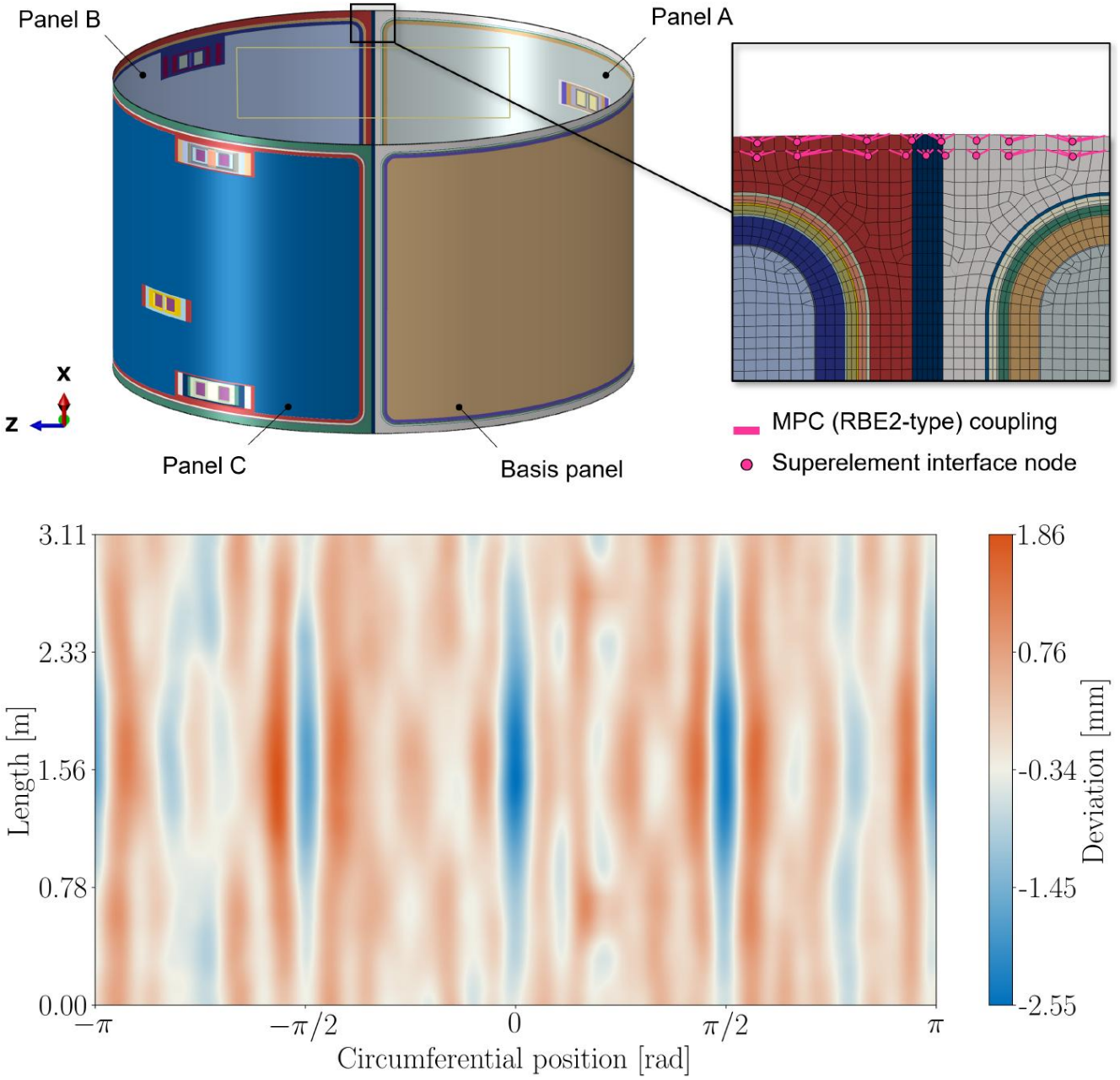


Figure 4 - Numerical modelling and assumed imperfection pattern for the Ariane 6 barrel.

3.3 Experimental VCT prediction in LC1

In LC1, the actual VCT load ratios were adjusted with respect to the measured experimental buckling load. The considered steps covered approximately 2%, 30.5%, 42.7%, 54.9%, 61.1%, 67.2%, 73.3%, 79.4% and 85.5% of the experimental buckling load. The spectra revealed clear modal shifts after the local buckling event. Certain modes disappeared or changed amplitude, and persistent external signals around 24-25 Hz overlapped with the low-frequency range predicted numerically. These observations underline that the application of VCT at full scale requires not only curve fitting but also careful modal interpretation, filtering of spurious peaks and recognition of local structural changes.

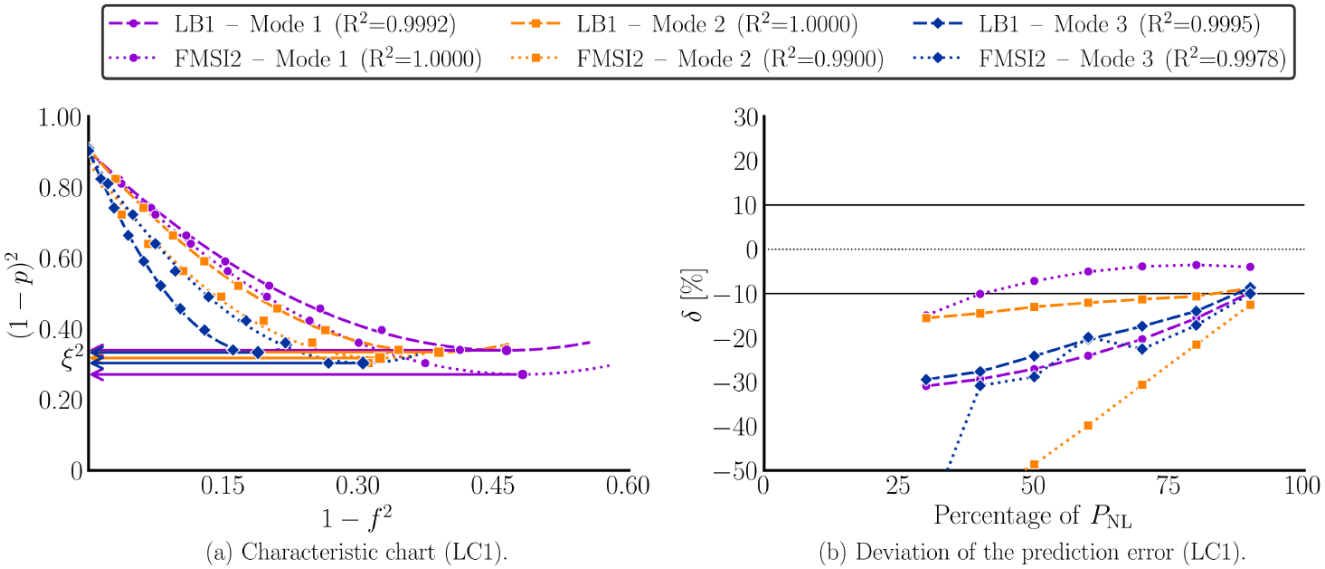
The VCT evaluation in LC1 focused on Modes 1 and 5, which were tracked in situ because their responses were of sufficient quality. Mode 5 delivered the most accurate estimates. At load steps up to 79.4% and 85.5% of the experimental buckling load, the deviations were -5.6% and +4.3%, respectively. The first value was conservative and very close to the reference load, while the second became slightly

non-conservative at the highest step, likely influenced by the local buckling history and the proximity to the global instability. Mode 1 was more conservative, with deviations of -20.9% and -14.8% at the same high load levels. From an engineering point of view, this result is highly significant: a mode identified in situ during a full-scale qualification campaign provided an error band close to the level expected from much more controlled VCT studies.

3.4 Experimental VCT prediction in LC2

LC2 involved a different actuator configuration and a different loading path. The measured global buckling load was 356 kN, with local buckling detected at 345 kN. The adjusted VCT steps reached approximately 83.8% of the experimental buckling load. Modes 2 and 12 were monitored in situ, while Mode 22 was identified during post-test assessment as an additional higher-order candidate. In contrast to LC1, the alternative preloading strategy adopted for LC2 produced measurements that were less disturbed by premature local-buckling effects over the range used for VCT assessment.

For LC2, the VCT predictions remained conservative. At 76.9% of the experimental buckling load, the deviations were -12.9%, -23.8% and -20.1% for Modes 2, 12 and 22, respectively. Mode 2 delivered the best prediction among the considered candidates. The numerical investigation had already suggested that LC2 would be more sensitive to the maximum load ratio used for extrapolation, and this behavior was confirmed experimentally: the prediction error decreased more rapidly as higher load steps were included. The inclusion of Mode 22 is important because it demonstrates that higher-order modes can remain useful for VCT, provided that they are correctly identified and tracked. This observation also connects the Ariane 6 study with the cylinder studies [5,6], where multi-mode evaluation is recommended as a way to detect outliers and stabilize predictions (cf. Fig. 5).



(a) Characteristic chart (LC1). (b) Deviation of the prediction error (LC1).

Figure 5 – Numerical VCT results for Ariane 6 LC1, including characteristic charts and prediction-error evolution.

3.5 Significance for qualification testing

The Ariane 6 study provides evidence that VCT can be integrated into qualification-relevant testing without forcing the structure to buckle during the initial stages of the campaign. The method delivered reliable predictions under combined axial-bending loading, multi-actuator load introduction and realistic boundary conditions. This is a considerable advance beyond laboratory validation on small shells. It also clarifies the practical conditions required for reliable implementation: the maximum load ratio should be high enough to condition the extrapolation, the frequency resolution must be sufficient to separate close peaks, and the selected vibration mode must remain physically meaningful over the considered load interval.

The results also show that high coefficients of determination for the quadratic fit are useful but not sufficient. A smooth curve can still be based on a mode affected by local buckling, measurement interference or an incorrect modal branch. Reliable VCT therefore requires a combined assessment of

fit quality, modal consistency, MAC-type tracking, visual inspection of mode evolution and engineering awareness of local instability events. The Ariane 6 campaign demonstrates that, when these elements are combined, VCT becomes a practical tool for in-situ assessment of real launcher hardware.

4. Multimodal verification of the payload fairing panel

4.1 Role of the payload fairing panel study

The second industrially relevant case is the curved CFRP/aluminium honeycomb sandwich panel representative of the Cable Connector Door region of industrial payload fairing [7] (cf. Fig. 6). The future research direction may be extended towards payload fairing structures more broadly; however, the experimental study discussed in [7] specifically concerns the industrial payload fairing panel. This panel contained features typical of industrial fairing hardware: sandwich construction, local reinforcements, inserts, connection details and a thermal protection layer. Such details make the dynamic response more complex than that of an ideal cylinder, and they also make numerical validation more demanding.

The purpose of this study was not to deliver a final VCT buckling prediction. The applied load range was sufficient for multimodal verification but too low for robust critical-load extrapolation. Instead, the work established whether a complex industrial panel could be characterized by load-dependent vibration measurements, whether the FE model could reproduce the measured stiffness and modal trends, and whether candidate modes could be tracked reliably under compression. This makes the study a bridge between model validation and future VCT implementation on fairing panels.

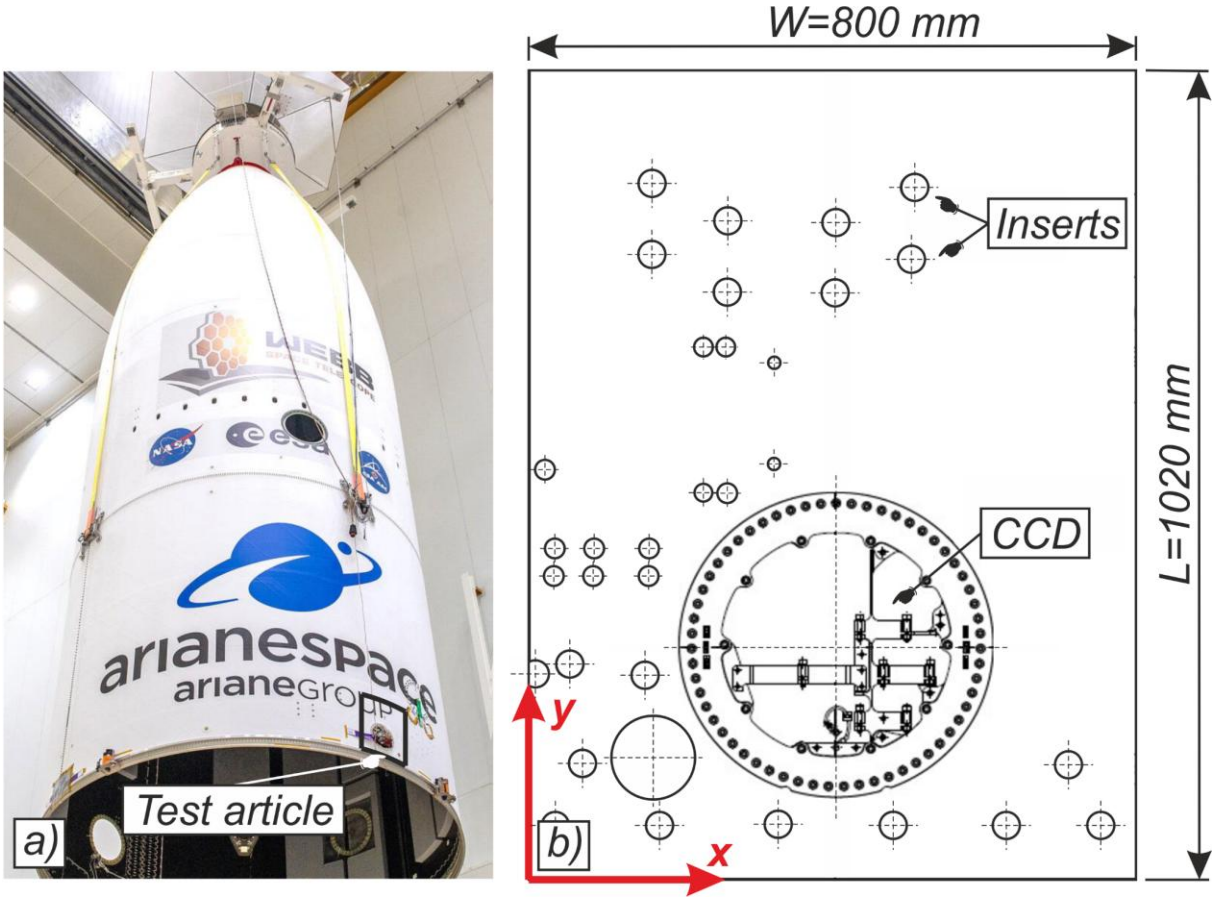


Figure 6 - Considered payload fairing panel and investigated region.

4.2 Experimental procedure and mode tracking

Two experimental configurations were used. In the first, vibrations were excited on the outer side and measured on the inner side. In the second, the excitation and measurement sides were reversed. The panel was loaded stepwise, with vibration measurements performed at constant load levels. Acoustic excitation was applied by a loudspeaker and the vibration velocity was recorded by a scanning laser vibrometer.

The modal identification provided particularly convincing results. Among the first 15 modes predicted numerically, 13 were identified experimentally. Ten modes were consistently tracked on both sides of the panel. The spectra measured on the inner and outer sides were highly similar, and corresponding natural frequencies differed by no more than 1 Hz. The average MAC values were 0.938 for the inner-side measurements and 0.965 for the outer-side measurements, with most tracked modes above the typical 0.9 threshold. Even when some local MAC values dropped to slightly above 0.6, the smooth evolution of the curves and visual inspection supported reliable mode assignment.

One important observation was mode splitting. The response associated with one of the modes separated into two closely related frequency branches under increasing load, while the mode shapes remained strongly similar. This type of behavior is highly relevant for VCT because the method depends on following a consistent mode branch. The payload fairing panel therefore provides a useful example of why multimodal tracking should combine spectral information, MAC values and visual assessment of mode shapes rather than relying only on peak frequencies (cf. Fig. 7).

The key observation, however, was the confirmed presence of a bending mode which, in the numerical analyses, led to very accurate VCT-based critical-load predictions. Experimentally, the frequency evolution of this mode at the highest considered load (around 20% of critical buckling load) was found to almost coincide with the measured response, indicating its potential relevance for future VCT-based buckling-load estimation.

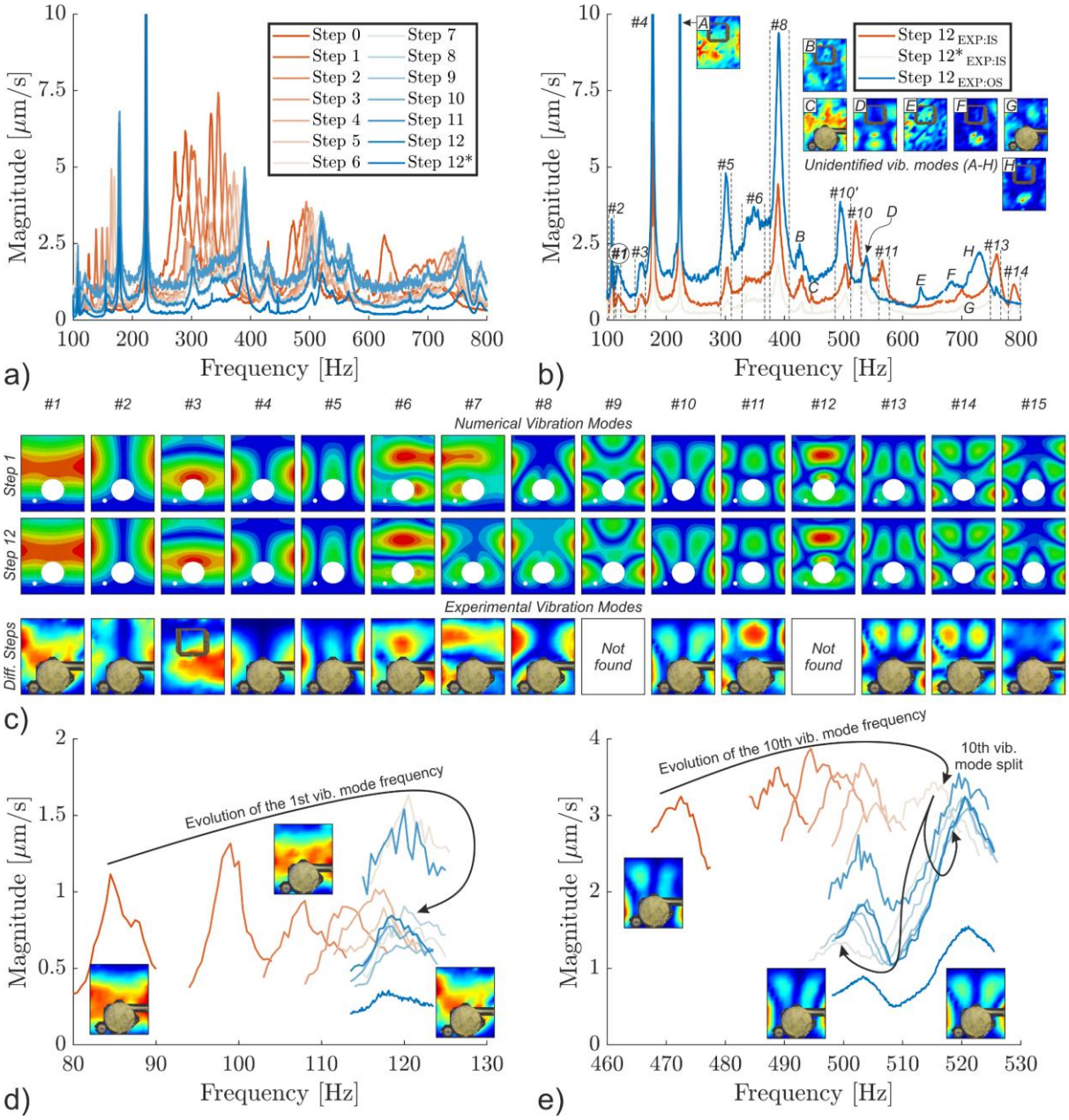


Figure 7 - Multimodal identification and tracking for the payload fairing panel.

4.3 Numerical validation and VCT relevance

The FE model reproduced both the quasi-static behavior and the load-dependent frequency trends with good accuracy. The initial nonlinear part of the load-shortening response was attributed to the elimination of clearances in the loading chain, which also influenced the initial frequency evolution. After this settling stage, the frequencies stabilized and then decreased at higher load levels, in qualitative agreement with VCT expectations. This behavior is important because it shows that industrial panel tests may contain initial frequency increases that do not invalidate VCT but must be separated from the subsequent trend used for buckling extrapolation.

The first bending mode was identified on both sides of the panel and is considered a promising candidate for future VCT-based buckling prediction. However, the study correctly concluded that the applied load range was too limited for a reliable prediction of the buckling load. This is a useful negative result: multimodal verification can validate the model and the measurement chain, but VCT requires sufficiently high load levels to condition the extrapolation. The practical outcome is that a future

dedicated campaign on payload fairing panels should use the same measurement logic but extend the load range toward the region where frequency reductions become more pronounced.

From an industrial perspective, the measurement procedure was efficient. Prestressed and non-prestressed vibration measurements could be completed within a single testing day. This matters for large-scale aerospace campaigns, where access to the test facility is limited and test slots are planned far in advance. The payload fairing panel study therefore supports a broader message: VCT-related modal testing can be used not only for direct buckling prediction but also for fast experimental validation of complex numerical models before critical load cases are executed.

5. Alternative approaches for non-conservative VCT estimates in unstiffened cylinders

5.1 Motivation for modifying the standard Arbelo chart

The standard Arbelo-type procedure is robust in many cases, but it is not immune to non-conservative predictions. This is particularly important for unstiffened CFRP cylindrical shells, where small differences in measured imperfection maps can change the relation between the nonlinear buckling load, the reference critical load and the measured frequency evolution. In a qualification context, a non-conservative prediction is more problematic than an overly conservative one because it may lead to an unsafe estimate of the remaining load margin. The recent cylinder studies therefore investigated whether selected modifications can reduce this risk while preserving the practical simplicity of VCT.

The modifications considered in [1], [5] and [6] do not replace the Arbelo concept. Rather, they examine the parameters used to construct the characteristic chart. These include the critical load used for normalizing the applied load, the unloaded natural frequency used for normalizing the frequency response, and the relation between the vibration mode and a corresponding analytical bifurcation load. The studies show that the standard chart should remain the first choice in most cases, but that additional tools are useful when the prediction curves display systematic non-conservative behavior or when imperfection characteristics suggest an outlier response.

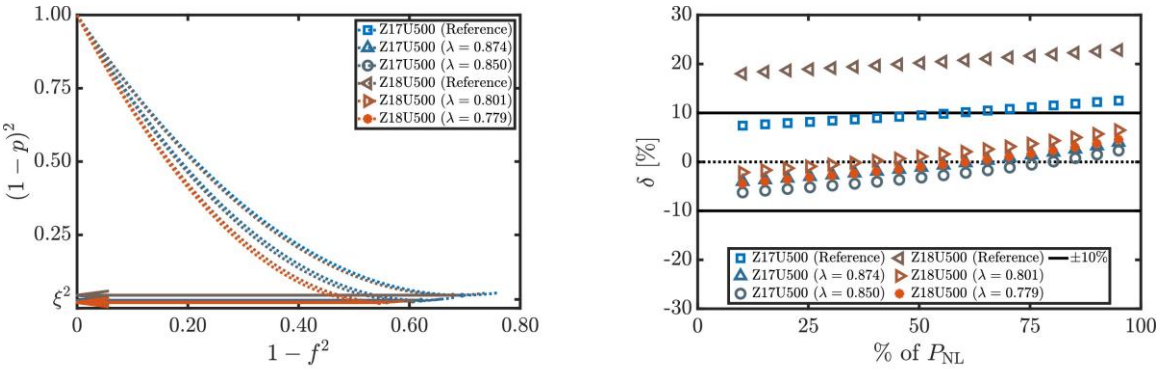
5.2 Lambda factor approach and observation of the KDF

The enhanced VCT proposed in [1] introduced a load factor, denoted here as lambda, to adjust the reference linear buckling load used in the characteristic chart. The concept is based on the observation that the convergence and conservativeness of VCT predictions are related to the KDF level to be estimated. In the numerical study on unstiffened composite cylinders, most specimens produced conservative and accurate predictions when the effective KDF was in a higher range. Two cylinders, Z17 and Z18, were associated with lower KDF values and delivered non-conservative VCT estimates with larger deviations.

The lambda factor modifies the critical load used in the normalized load parameter. By selecting lambda so that the effective KDF is shifted into a range associated with reliable convergence, the non-conservative predictions can be moved toward the conservative side. For Z17 and Z18, applying the proposed load factors transformed previously non-conservative estimates into predictions very close to the nonlinear buckling loads. The reported deviations after modification were around -0.23% to -0.59% for Z17 and around -0.20% to -0.14% for Z18 in the considered cases. This is a strong indication that the load normalization parameter can control the practical behavior of the characteristic chart (cf. Fig. 8).

The approach was also assessed on an additional experimental cylinder, R08. The load factors were selected using numerical studies and then applied to experimental VCT data. The modified predictions became conservative, and in most cases their absolute deviation was reduced. The central message of [1] is therefore not that a universal lambda value exists, but that monitoring the KDF range and using numerically supported load factors can enhance VCT when the standard chart is expected to be non-conservative. The lambda factor approach should therefore be interpreted as a corrective extension of the Arbelo-based formulation for selected cases in which the conventional characteristic chart may lead to non-conservative estimates. Its purpose is not to replace the standard VCT procedure, but to improve

the reliability of the prediction in imperfection-sensitive shells by accounting for the observed relation between the estimated KDF and the evolution of the vibration response.



(a) Modified characteristic chart. (b) Convergence of the relative deviation.

Figure 8 – Modified characteristic chart and determined predictive curves based on lambda factor approach.

5.3 Robustness under scaled and inverted imperfection maps

The robustness study [5] extended the analysis to ten CFRP cylinders with measured mid-surface and thickness imperfections. The imperfection maps were not only used in their original form but also scaled and inverted. This created a broad numerical dataset for evaluating how VCT behaves when imperfection amplitude and direction are manipulated. Four variants of the Arbelo chart were examined. Versions 1 and 2 used alternative definitions of the unloaded natural frequency and proved unsuitable, producing large errors or unstable predictions. Their failure is instructive because it shows that even a small discrepancy in the unloaded natural frequency can strongly disturb the characteristic chart.

The classical approach (Version 3), corresponding to the standard Arbelo-type procedure, and the modified approach (Version 4), where the reference critical load is replaced by the critical load predicted by the numerical model with measured geometric and material imperfections, both yielded valid VCT-based predictions over a wide range of imperfection scenarios (cf. Fig. 9). Conservative prediction basins were clearly visible, and the method remained stable even when imperfection amplitudes were varied. Original and inverted imperfection maps did not produce symmetric results, but their deviation distributions were broadly comparable. This indicates moderate sensitivity to imperfection direction but a generally robust response of the VCT framework.

A notable outcome was the behavior of cylinder Z18. Its nominal imperfection map fell within a non-conservative prediction region, unlike most other cylinders. This confirms that manufacturing accuracy cannot be reduced to a single amplitude parameter; the spatial distribution of imperfections can determine whether the standard VCT prediction is conservative. The study also introduced normalized gradient maps to detect abrupt changes in prediction accuracy across the parameter space. Such anomalies were often linked to cases in which local buckling preceded global instability and disturbed the modal branch used in the characteristic chart. The anomalies can sometimes be mitigated by adding predictions from higher-order vibration modes.

The comparison between Version 3 and Version 4 led to a balanced conclusion. Version 4 was statistically more conservative in almost all cases, which is useful when safety margins dominate the decision. However, it was not systematically more accurate. In many cases, the standard approach delivered a better combination of accuracy and conservativeness. Consequently, the classical approach (Version 3) should remain the practical baseline. The modified approach is best interpreted as an optional conservative variant for selected cases, especially when prior numerical analysis or imperfection indicators suggest that the standard chart may be non-conservative.

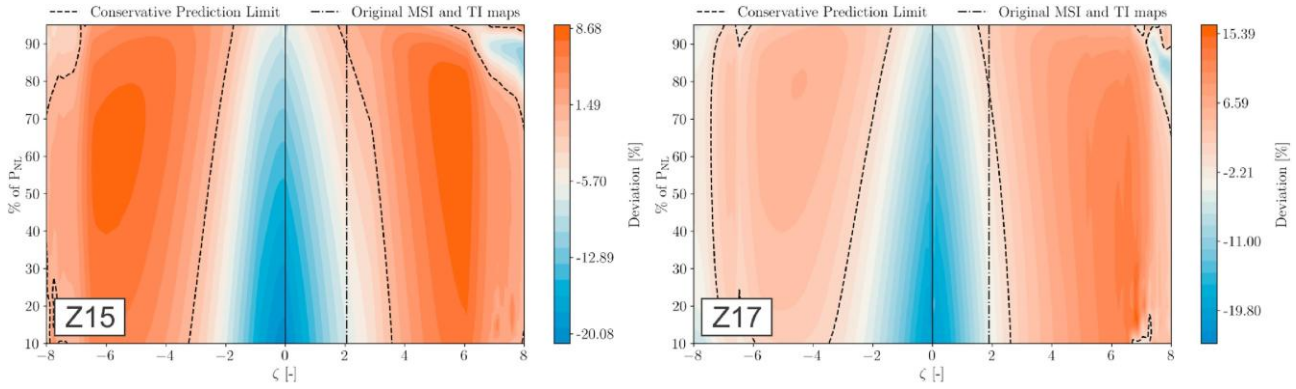


Figure 9 - Robustness of VCT under scaled and inverted imperfection maps, including standard (Version 3 - LHS) and modified (Version 4 - RHS) Arbelo-type approaches.

6. Double-curved shells and future extension of VCT

6.1 Imperfection strategies for double-curved shells

The double-curved shell study [3] did not apply VCT directly, but it is highly relevant for defining the next stage of VCT development. The work investigated isotropic and composite toroidal shell segments under compression, using geometries derived from previously studied cylinders and cones. The radius at mid-height was modified from 0.8 to 1.2 of the nominal value, creating concave and convex doubly curved variants. Three classes of imperfections were introduced: measured mid-surface and thickness imperfections, LBMI and SPLI. This provided a comparative framework for evaluating load-carrying capacity, knock-down factors and postbuckling behavior in structures more complex than cylinders or cones.

Several results are directly relevant for future VCT. First, a slight convexity of composite doubly curved shells increased load-carrying capacity relative to the corresponding nominal cone or cylinder. Second, some concave structures exhibited a behavior closer to imperfection-insensitive response, with nonlinear load-carrying capacity exceeding the linear critical buckling load. Third, the imperfection method mattered. LBMI generally delivered the most conservative KDF estimates, whereas SPLI produced KDF values close to those obtained from measured MSI, usually with a slight conservative bias. This suggests that the three approaches provide complementary bounds rather than interchangeable representations.

For convex structures, effective KDF values could be determined using MSI, LBMI and SPLI. The KDF values from measured MSI were close to SPLI results, while LBMI served as a lower-bound-like estimate. In composite structures, the most detrimental LBMI did not necessarily correspond to the first buckling mode. Circumferentially aligned buckling modes were more efficient in degrading membrane stiffness and therefore produced more conservative KDF values than axially oriented patterns. These findings are important for VCT because they indicate that the vibration mode most relevant for prediction may not be the lowest mode and that mode orientation can be decisive in complex curvature fields (cf. Fig. 10).

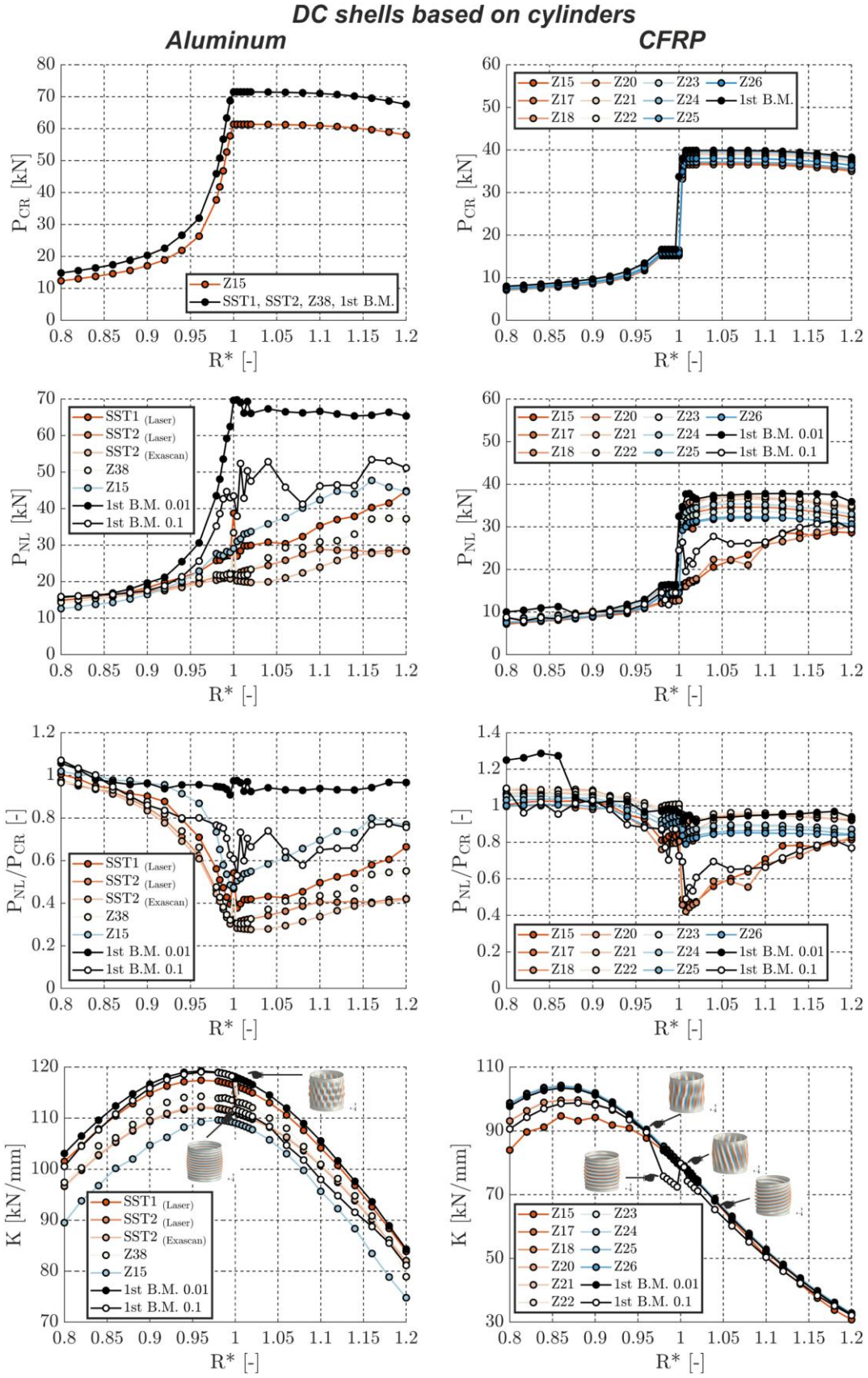


Figure 10 - Linear buckling loads (P_{CR}), load carrying capacities (P_{NL}), P_{NL}/P_{CR} and stiffness K for isotropic and composite DC shells based on Z-cylinders geometry.

6.2 Potential applicability spectrum for VCT

Although VCT was not yet applied directly to the double-curved structures in [3], the study identifies a potential spectrum of applicability. Cases with stable and continuous prebuckling response, clear modal evolution and a load-carrying capacity governed by a global instability are promising candidates. Convex structures may be especially attractive because their load-carrying capacity can exceed that of nominal cylinders or cones while still exhibiting measurable imperfection sensitivity. Concave structures that behave more like imperfection-insensitive shells may require a different interpretation, possibly closer to the classical VCT framework if the vibration and buckling modes become more strongly coupled.

The use of MSI, LBMI and SPLI also provides a basis for pre-test screening. Before a dedicated VCT campaign is performed, numerical studies can identify whether the structure is expected to buckle globally or locally, whether the critical modes are circumferentially or axially oriented, and whether a small set of vibration modes is likely to capture the relevant stiffness degradation. This can guide the selection of sensor grids, excitation frequency ranges and load steps. In this sense, [3] establishes a roadmap: the next step is to take the structures and imperfection scenarios that showed stable postbuckling paths and evaluate whether their load-dependent frequencies generate useful VCT characteristic charts.

6.3 Cut-outs, local degradation and local buckling

Future work should also move beyond geometrically smooth shells. Payload fairings, adapters and tank barrels contain cut-outs, doors, inserts, welds, joints, local reinforcements and local material or stiffness degradation. These details may initiate local buckling before global instability. The Ariane 6 study [8] already demonstrated that local buckling can modify the modal response and affect the final VCT load steps. In structures with openings or local degradation, this effect may become dominant rather than incidental. The key question is then how VCT behaves when the first instability is local, when local modes interact with global modes, or when a local stiffness reduction changes the unloaded natural frequency and the load-dependent modal path.

The proposed future direction is therefore to study structures with holes and local degradations in a controlled way. Numerical models should introduce local geometric defects, ply degradation, core damage, delamination-like stiffness reductions or local cut-outs, and the corresponding vibration response should be tracked under compression. The objective is not only to predict a global buckling load but also to determine whether VCT can identify the onset of local instability and whether its prediction remains conservative when local buckling precedes global collapse. If VCT is sensitive to local degradation through measurable modal changes, it could become a broader non-destructive tool for stability assessment of imperfect and damaged aerospace shell structures.

7. Consolidated assessment

The studies considered here form a coherent development path. The early laboratory-scale VCT research established the Arbelo characteristic chart as a practical formulation for imperfection-sensitive shells. The enhanced lambda approach [1] showed that the KDF range and the reference critical load can be used to correct non-conservative cases. The robustness study [5] clarified the role of imperfection amplitude, direction and normalization choices. The payload fairing panel study [7] validated load-dependent multimodal testing on a complex industrial sandwich structure. Finally, the Ariane 6 campaign [8] demonstrated that VCT can be used during a full-scale qualification-relevant test.

A consolidated interpretation of these results is that VCT is most reliable when three conditions are satisfied. First, the selected vibration modes must be tracked consistently, preferably using both MAC-type metrics and visual inspection. Second, the maximum load level included in the characteristic chart must be high enough to stabilize extrapolation, but low enough to avoid damaging the structure or mixing post-local-buckling data with the prebuckling trend. Third, the numerical reference quantities used for normalization must be chosen carefully and, wherever possible, validated against experimental modal data. When these conditions are met, VCT usually provides conservative or near-accurate

predictions. When one of them is violated, the method may still produce a smooth curve, but the physical reliability of the prediction decreases.

The structure of the paper follows the development path of VCT from its methodological foundations towards qualification-relevant industrial applications. The discussion first recalls the evolution of the characteristic charts used in VCT and then focuses on the experimental validation performed on the Ariane 6 test article. This case represents the most advanced demonstration of the method, showing that VCT can provide reliable non-destructive buckling-load predictions for a full-scale launcher structure under qualification-relevant testing conditions. The subsequent discussion extends the perspective to the multimodal experimental verification of a payload fairing panel, where vibration measurements under compression were used to validate the numerical model and to identify vibration modes potentially relevant for future VCT-based buckling-load estimation. The following sections then summarize recent developments aimed at improving the robustness of VCT for imperfection-sensitive cylindrical shells, including correction strategies based on modified characteristic-chart parameters and alternative definitions of the reference critical load. In this way, the paper shows that VCT has evolved from an empirical correlation concept into a non-destructive prediction tool with demonstrated industrial relevance, while current research continues to define its limits, correction strategies and future fields of application.

8. Conclusions

The consolidated results confirm that VCT has reached a maturity level that makes it relevant for non-destructive buckling prediction of thin-walled launcher structures. The decisive advance is the Ariane 6 validation [8], where VCT was successfully applied to a full-scale test article under qualification-relevant combined axial-bending loading. This proves that VCT can operate outside ideal laboratory conditions and can provide useful information during industrial test campaigns.

The Ariane 5 payload fairing panel study [7] complements this result by showing that load-dependent multimodal vibration measurements can validate complex industrial sandwich structures. Although the load range was not sufficient for a reliable buckling prediction, the identification of 13 out of 15 numerical modes, consistent tracking of 10 modes on both sides and close agreement of frequencies between inner and outer measurements establish a strong experimental basis for future VCT on fairing structures. This work is particularly important for structures with local details, thermal protection layers and realistic boundary conditions.

For unstiffened CFRP cylinders, the standard Arbelo-type classical approach remains a robust and practical baseline. The method is generally conservative, especially when multiple low-order modes are considered and the maximum load level approaches the upper prebuckling range. However, the studies also show that some imperfection maps, most notably Z18, can lead to non-conservative estimates. In such cases, targeted modifications are justified. The lambda factor [1], the modified Arbelo normalization [5], and the analytical bifurcation or analytical critical load approaches [6] provide a hierarchy of corrective tools. Their use should be guided by numerical evidence, imperfection-map indicators and multi-mode consistency rather than applied automatically.

The double-curved shell study [3] defines the next frontier. By comparing MSI, LBMI and SPLI on concave and convex toroidal shell segments, it identified structural regimes that may be suitable for future VCT and clarified the role of mode orientation, imperfection source and curvature. Future research should translate this stability assessment into actual load-dependent vibration predictions. In parallel, structures with cut-outs and local degradation should be studied because local buckling may occur before global collapse and may strongly affect the characteristic chart. The next generation of VCT research should therefore combine multimodal experimental tracking, imperfection-map descriptors, local instability detection and modified reference-load strategies into a unified non-destructive stability assessment framework.

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