GUIDELINES FOR TEST CONDITIONS AND DOCUMENTATION OF BUCKLING EXPERIMENTS WITH CYLINDRICAL CFRP SHELLS

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ABSTRACT

Different types of loads, such as axial compression, torsion or bending, cause thin-walled cylindrical shells to collapse due to buckling. Because of numerous kinds of possible imperfections, this usually occurs significantly below the buckling load of the ideal shells. When using fibre composites, there are even more influencing factors. Therefore, test data are indispensable for the design of new shells. This data is needed to validate models and new design approaches. However, the available database remains a major challenge. Many experimental data are not freely accessible or were generated under different conditions. Thus, in this contribution, the available database is gathered and evaluated. Differences and irregularities are identified. In particular, the accessibility of geometric imperfections is weak. Although there is an imperfection database, the access to it is very limited. Subsequently, it is shown which data the most widespread or common design approaches require. Based on the analysis of the available database as well as the required data for the individual design approaches, recommendations for testing thin-walled cylindrical composite shells and for publishing new test data are formulated. These include suggestions for the type and extent of publication of the experimental data. For geometric imperfections, for instance, the use of Fourier coefficients is recommended. For load imperfections, scalar data is sufficient. Existing boundary conditions and other imperfections should be measured and documented. Finally, a test series of 12 thin-walled CFRP cylinder shells is used to show how these recommendations are to be applied. It is illustrated that the scatter varies depending on the quality of the test, thus underlining the importance of profound documentation of test procedures, setup and results.

1 INTRODUCTION

Thin-walled cylindrical composite shells are commonly used elements in aerospace engineering. This field of application results in high requirements regarding the weight and reliability of these shells which are prone to buckling under critical loads, such as axial compression, bending and torsion as well as combinations of those load cases [1, 2]. Due to the sensitivity of the buckling load to a variety of different influencing factors, there is a significant discrepancy between the theoretical, analytical buckling load and the one observed in tests. The most prominent factors known to influence the buckling load are the geometric imperfections of a shell, material properties, laminate layup, boundary conditions and load imperfections that occur during experiments [1, 3–5]. While the influence of these parameters has been thoroughly demonstrated qualitatively in theory and experiments, specific measurement data are often not easily accessible. A number of design approaches has been developed in the past to achieve reliably conservative designs under axial compression loads without undermining the lightweight design potential of these structures, e.g. [1, 5–7]. However, as there are only limited experimental data available in literature, a new approach is often developed and validated on the same set of data. Regarding combinations of different buckling inducing loads, even fewer data sets are found in literature, most of which consider only combined torsion and compression loads, e.g. [8, 9].

Across the test campaigns with composite shells found in literature, starting with Tasi et al. [10] in 1965, a few best practices have been established for testing and the publication of experimental results, although there is no standardised procedure or clear guidelines for either. Hence, the extent of the documentation varies greatly between different published studies, raising the question of the consistency of quality between the experimental data. Even when considering only test campaigns with profound documentation, there are some significant differences in test procedures, the recorded data and the documentation thereof to be observed. While the published data are often used by means of example or for validation of numerical models, the testing conditions are rarely critically reviewed, even though it has been shown that the boundary conditions, the test setup and the test rig itself can significantly influence the buckling behaviour, e.g. [9, 11, 12].

Consequently, this contribution aims to provide a means of support for the generation of more consistent and thus better comparable experimental data on the buckling of composite shell structures in the future.

2 METHODOLOGY

In a first step, a comprehensive database of published buckling experiments with cylindrical composite shells is compiled, based on the already extensive data presented in [13–16]. These data sets are expanded on by a literature review in SCOPUS using the core search string *"Buckling" AND "Experiment" OR "Test" AND "Cylindrical" AND "Composite" AND "Shell"*. In order to achieve a reasonable comparability between the collected data, only unstiffened shells made entirely of fibre/plastic composites are considered while any composite sandwich shells are excluded. Furthermore, only data from experiments under pure axial compression load are included, as there are only very few published studies considering torsion, bending or combined loading, resulting in a low comparability.

The dataset is then analysed with respect to its composition, the commonly recorded data as well as the major differences in documentation between publications. Following that, a number of existing design approaches for cylindrical composite shells under buckling inducing loads are investigated regarding the data and information necessary for their application. The considered design approaches include the most widely established ones, the NASA-SP-8007 [1] and the perturbation approaches, exemplified on the Single Perturbation Load Approach (SPLA) [5]. At the same time, other commonly known deterministic procedures [17, 18] and probabilistic approaches [6, 7, 19] are considered for the purpose of covering a wide range of different procedures. Based on the review of the compiled data and the analysis of approaches for modelling, simulation and design of such shells, a set of guidelines for test campaigns is developed to support future experimental research in the field of buckling critical composite shells.

The derived recommendations are then applied in an experimental test campaign with 12 cylindrical CFRP-shells, in order to demonstrate the validity of these guidelines. This includes the use of defined, identical boundary conditions for multiple tests, recording and quantifying loading imperfections such as lateral forces and tilting of the shells, as well as measurement of geometric imperfections of all tested shells. The test conditions, setup and procedure are thoroughly documented and published including the gathered data and all experimental results.

3 REVIEW OF PUBLISHED EXPERIMENTAL DATA

3.1 Description of the database gathered from literature

Reviewing the existing literature on buckling experiments with cylindrical composite shells under axial compression yields a total of 206 shells for which experimental data have been documented. The gathered database is available on the open access repository Zenodo.org [20] and will be continually updated in the future as new experimental data are published. In its first version, the database includes a total of 32 studies from as early as 1965 [10] up to the present day [21, 22].

Each individual tested shell is listed with its designation, geometric specification, stacking sequence and material parameters, to the extent those data are provided. The data included to fully describe the geometry are the inside radius R, the wall thickness t, the total length L and the free length L_{free} that remains after mounting the shell in the test setup. Additionally, the lamina thickness is given, either as documented in the respective studies or calculated based on total wall thickness and stacking sequence. As the database includes only fibre/plastic composite shells, the material properties listed for each shell consist of the Young's moduli in longitudinal and transverse direction E_{11} and E_{22}, the in-plane shear modulus G_{12} and the major Poisson's ratio v_{12}. If both nominal and measured data were published for geometry or material parameters, only the measured ones were included into the database.

The existing test data cover a wide variety of different R/t-ratios ranging from 20 to 893 with the majority of tested shells to be found at ratios between 100 and 400, as visualised in Fig. 1 (left). However, when considering only the radii of the shells as given in Fig. 1 (right), it is apparent that a significant number of the existing cylinders have a radius of either 100 mm or 250 mm. Furthermore, out of the 44 shells with a radius of 250 mm, 37 were manufactured at the German Aerospace Centre (DLR) Braunschweig, two shells were produced at Riga Technical University (RTU) [23] while for the remaining five specimens the manufacturer could not be determined.

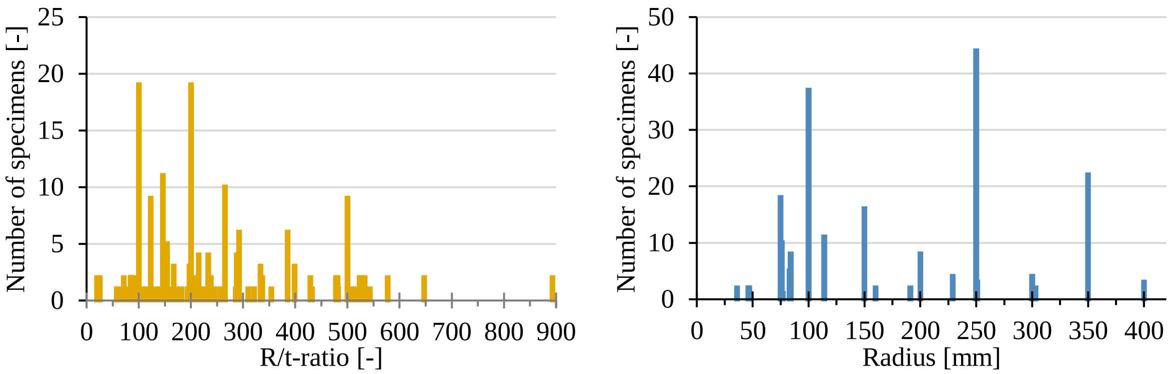

Figure 1: R/t-ratios of shells in database (left); Radii of shells in database (right).

In cases where multiple tests were conducted with a single shell, only the first valid buckling load is included in the database for that shell. Similarly, any shell that has been repeatedly tested in multiple publications in the same test setup is only listed once. Furthermore, information on the test rig boundary conditions and the test rig itself as well as the manufacturing process and the manufacturer are compiled, although the extent of documentation regarding these data greatly varies between publications.

3.2 Analysis of the compiled database

In this section, the gathered database is analysed regarding the data and information included therein and the differences in the extent of documentation as well as discrepancies between publications are outlined.

Commonly, in publications on buckling experiments the nominal shell geometry is documented for the investigated specimens, specified with radius R, wall thickness t and length of shell L. In some cases, e.g. [24], the wall-thickness or length is only given indirectly through the R/t or L/R ratios. While most publications do mention the difference between the total length of a shell and the free length that remains after mounting the specimens in the test set up, there are some studies where only one of these measurements is documented. Although it is commonly known that shells with a higher slenderness exhibit increased sensitivity to the numerous influences and imperfections [1, 25], only few shells with R/t-ratios larger than 500 have been investigated in literature. Furthermore, in the majority of studies less than four nominally identical shells are tested. Consequently, no well-founded statements regarding the stochastic nature of either the numerous influencing factors nor the resulting buckling loads can be made. Notable exceptions are two studies, one by Degenhardt et al. [4] in which ten nominally identical shells were tested and one test campaign by Schillo et al. [26], who investigated eleven identical specimens.

It is stated in several studies, e.g., [4, 5, 8, 9] that the geometric imperfections of the investigated shells were measured, as these are one of the major influence factors on the buckling load. However, very few imperfection data have been published readily accessible, e.g., in the form of Fourier coefficients in [27].

The majority of publications within the database contain a list of nominal material properties of the composites used to manufacture the investigated shells. These usually include the Young's moduli in longitudinal and transverse direction E_{11} and E_{22}, the in-plane shear modulus G_{12} and the major Poisson's ratio ν_{12}. However, there are also some studies that do not contain values for some of these parameters. Several experimental campaigns specify the material utilised as an IM7/8552 CFRP prepreg system. However, as noted in [4] and shown in Table 1, in some cases the documented material properties differ significantly between studies. Some publications state different values for the longitudinal Young's modulus E_{11} under tension and compression load, e.g. [4, 23] while many others do not specify which type of loading is considered. While there are only tensile stiffness properties listed in Table 1 and [20] in order to retain comparability between the different studies, there can be a significant difference between tensile and compressive stiffness.

Author, Reference	t_{Layer} [mm]	E_{11} [GPa]	E_{22} [GPa]	G_{12} [GPa]	ν_{12} [-]
Degenhardt et al. [4]	0.125	175.30	8.60	5.30	0.30
Lincoln et al. [21]	0.131	138.00	9.72	4.69	0.36
Rudd et al. [22]	0.175	140.90	9.72	4.69	0.36
Skukis et al. [23]	0.125	171.50	8.90	5.10	0.32
Bisagni [11]	0.125	150.00	9.08	5.29	0.32
Kalnins et al. [28]	0.131	150.20	9.40	5.10	0.32
Khakimova et al. [29]	0.125	152.40	8.80	4.90	0.31
Span	0.050	37.30	1.12	0.61	0.06

Table 1: Comparison of material properties of IM7/8552 Prepreg.

In most cases where test rig boundary conditions are explicitly described, the shells are affixed in a fully clamped manner at both ends as visualised in Fig. 2 (right), e.g. [4, 5, 22]. Some studies utilised connection elements like ball joints on one or both ends of the cylinders, resulting in a so-called simple support which is shown in Fig. 2 (left) that allows for tilting of the shell, e.g. [25, 26, 30]. However, there are also a number of studies that do not include any conclusive information on the clamping of the shells and test rig boundary conditions, diminishing the comparability of those data. This is of particular importance, as the test rig boundary conditions can also influence the occurring loading imperfections, as noted in [12].

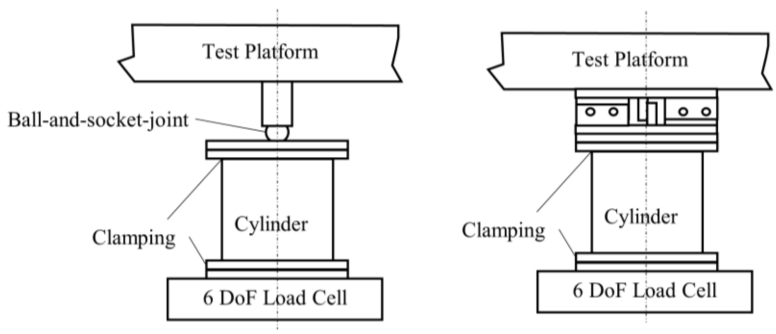

Figure 2: Different test rig boundary conditions, bottom fully clamped and top simply supported (left); Both shell edges fully clamped (right).

Although it has been shown that imperfections in load introduction, such as tilting or lateral forces, can have a significant influence on the buckling load and thus need to be considered in the validation of numerical models [7, 12, 31, 32], there are only few test campaigns in which the occurring load imperfections are recorded, e.g. [25, 26]. Additionally, while there are studies investigating the effects of combined loading on the buckling behaviour, the transition from uniaxial loads with loading imperfections to a multiaxial load case is not clearly defined. Particularly in case of multiaxial buckling experiments with controlled load combinations, information on the test rig boundary conditions and the stiffness of the clamping may well be essential to distinguish between loads introduced in a controlled manner and occurring load imperfections.

4 DEVEPLOPEMENT AND EXEMPLARY APPLICATION OF GUIDELINES

4.1 Derivation of guidelines for buckling experiments

As elaborated in the previous section, a broad scatter exists not only in the specifications and data of tested CFRP shells but also in the extent and the manner of how experimental studies have been documented in the past. The data from such test campaigns are often used as a basis for development and validation of numerical models, e.g. [9, 26, 33] or new design approaches, e.g. [5–7, 13].

In order to validate a numerical model (typically finite element models), the deviations from the ideal configuration have to be known, which are decisive for the buckling behaviour. These are typically geometric imperfections as well as imperfections in load introduction. This information is also required for design approaches which capture these influences by considering their stochastic nature, i.e., probabilistic approaches. Though, as previously noted, several studies state that geometric imperfections have been measured, they are not published in the majority of papers. One such exception is the work of Schillo [27]. Prof. Johann Arbocz, who dedicated his life to cylinder buckling, started an effort to collect geometric imperfection measurements in the Initial Imperfection Data Bank at the Delft University of Technology (see, e.g., [34, 35]). However, Prof. Arbocz was not allowed to published all collected data and hence, the limited published data do not include measurements of composite shells. The format for storing and sharing geometric imperfection measurements used in [27, 34, 35] is listing the coefficients of a double Fourier series. This way, the imperfections are given in a very condensed, mesh-independent way. Hence, it is suggested to use this established, universal format for documenting and sharing geometric imperfection data.

Regarding loading imperfections, the preferred format for describing and sharing the data is less obvious, due to the different phenomena that are captured under this terminology. Loading imperfection may refer to an inclination in the load introduction plane [7], to unintended lateral forces [26], or to geometric deviation at the shell edge in axial direction [36]. While inclination angles and lateral forces can be captured by scalars, edge imperfections should be described by Fourier series similar to geometric imperfections. Consequently, as loading imperfections can also greatly influence the buckling load, it is advised to record these data and publish them alongside the experimental results.

The validation of a design approach may require less data than the model validation, particularly when only a conservative lower bound shall be verified. An overview of design approaches and the required information is given in Table 2. Deterministic approaches like the knockdown factor approach followed in industry and suggested in NASA-SP-8007 requires only nominal data [1]. The same holds for perturbation based approaches, like the SPLA suggested in [5] and other approaches that attempt to find a lower bound of load carrying capacity based on defined geometric imperfections (see, e.g. [17]) or by controlled reduction of the shell energy or stiffness matrices [17, 18]. Pure probabilistic approaches, such as the ones suggested in [6] and [7] require not only measurement data, but also information on the scatter of the different parameters, while there are also hybrid approaches, as for instance the Probabilistic Perturbation Load Approach (PPLA) [19].

As visualised in Table 2, the most commonly published shell data, apart from the buckling load, are the same ones that are required for the application of deterministic design approaches. These data, the nominal geometry and laminate layup as well as nominal material properties and the boundary conditions, are usually known even before manufacturing and testing of the shells.

Information about investigated shells	**Commonly published data**	Validation of simulation models	NASA-SP-8007 [1]	Perturbation approaches, e.g. [5]	Linear buckling mode approach [17]	Energy- and stiffness-based approaches, e.g. [17, 18]	Probabilistic perturbation load approach [19]	Probabilistic approaches, e.g. [6, 7]
Nominal geometry	**X**		X	X	X	X		
Measured geometry		X					X	X
Nominal material properties	**X**		X	X	X	X		
Measured material properties		X					X	X
Boundary conditions	**X**	X		X	X	X	X	X
Scatter of geometry							X	X
Scatter of material properties							X	X
Geometric imperfections		X						X
Load imperfections		X					X	X

Table 2: Data required for model validation and application of exemplary design approaches

However, some essential data for the validation of numerical models or application of probabilistic approaches are not available in many cases. Both, the actual geometry and material properties usually deviate from the nominal values while having a significant influence on the buckling load. This is of particular importance in case of composite shells, as some geometry parameters, such as the measured wall thickness, may directly correlate with certain material properties [19]. Furthermore, as outlined previously, it has been shown that some CFRP composites do exhibit notably different stiffness under tensile or compressive loads. Consequently, in many cases it is challenging to utilise published shell data for validation of simulation models in numerical investigations. Similarly, applying probabilistic approaches to the shells of published studies or using such data for validation of new approaches is only possible in very few cases, as often no information on the scatter of the different parameters is given.

Hence, it is advised to not only measure and document the deviation to the nominal geometry of the specimens investigated in any test campaign, but also to determine the material properties of the used composite and the scatter of these parameters, for example by conducting coupon tests. In addition, to gain some knowledge of the scatter of the shell geometry and geometric imperfections, it is recommended to investigate multiple nominally identical shells, if possible, at a sample size large enough to allow for statistically backed estimates of distributions.

4.2 Proposal of guidelines for buckling tests with composite shells

Several recommendations were outlined as a result of the analysis of the available database on buckling tests with composite cylindrical shells in combination with the use of these data for validation of numerical models and in different types of design approaches. While there are numerous studies that follow certain established best practices regarding the basic information, the majority of data necessary for further use of the test results in a scientific context is not published consistently.

Thus, to increase the comparability between experimental studies, the following guidelines for test conditions and procedures in buckling experiments with composite shells, as well as the publication of such studies are proposed.

1. The nominal geometric specification of each shell must be documented. For cylindrical shells, this includes the inside radius, wall thickness, the total and the free length of the shell and the

laminate stacking sequence. Differences in measured geometric specifications between nominally identical shells and deviations from the nominal geometry should be documented.
2. The utilised fibre/matrix system shall be specified, as well as the manufacturing process and the material properties necessary for FE-modelling. These include the Youngs' moduli in longitudinal and transverse direction E_{11} and E_{22}, the in-plane shear modulus G_{12} and the major Poisson's ratio ν_{12}. If possible, the parameters E_{11} and E_{22} should be given separately for tensile and compressive stiffness. For better comparability between test campaigns, the use of a commonly known fibre/matrix system and documentation of the manufacturer is advised.
3. A description of the utilised test rig, the test setup and the test rig boundary conditions for the experiments shall be given, particularly of the clamping at the shell edges. Additionally, the stiffness of the test setup should be documented if it is known or if it can be estimated.
4. The geometric imperfection pattern of each shell should be measured after clamping and published in a way that is readily available and suitable to be used for validation of numerical models, for example in the form of Fourier coefficients or as raw data.
5. The load types applied in a controlled manner during the experiments (e.g., axial compression, positive or negative torsion) must be specified. Additionally, the type of loading (e.g., load-controlled or displacement-controlled) and the speed of loading should be documented.
6. It is advised for a minimum of three nominally identical specimens to be investigated in test campaigns, with each shell being tested multiple times in order to better identify outliers and anomalies.
7. The achieved buckling load shall be documented for each shell. If a specimen is tested multiple times, the buckling load of the first test should be specified and either the values or the scatter of buckling loads from subsequent tests should be documented.
8. Occurring load imperfections, such as for example tilting of the shell, eccentricities or lateral forces, should be recorded and documented.

It is advised to follow these recommendations in order to achieve a profound documentation of the conducted buckling experiments that enables other researchers to utilise the generated data in future investigations or the validation of simulation models and design approaches.

4.3 Application of the developed guidelines in an experimental study

The proposed guidelines for buckling experiments and the documentation thereof were applied during a test campaign with 12 CFRP shells of nominally identical geometric specification and laminate stacking sequence. One half of the investigated shells was manufactured layer-by-layer with semi-automatic hand-layup, the other half in a filament-winding process, resulting in two sets of six nominally identical specimens. The cylinders have a nominal radius of 115 mm, a total length of 255 mm and a free length of 215 mm after clamping. An AS7/8552-Prepreg was used as the fibre matrix system. The material properties were determined by way of coupon tests, described in [37]. The laminate lay-up for the hand-laminated cylinders is [90°,-30°,30°,-30°,30°,90°] and for the wound ones [90°,-30°,30°]s, resulting in a nominal wall-thickness of 0.78 mm. The nominal R/t ratio is 147 for both sets of shells. Based on photogrammetric measurements and numerical analyses, the load carrying wall thickness was determined to be about 0.7 mm for the layered shells, while for the filament-wound cylinders values scatter between 0.73 mm and 0.77 mm. A detailed description of the shells and this test campaign is given in [33].

The experiments were carried out on the Hexapod test rig at the University of Technology Hamburg (TUHH), shown in Fig. 3, and a modified Galdabini Quasar 100 universal testing machine (UTM) as well as the well-known buckling facility of the German Aerospace Centre Braunschweig (DLR). The axial stiffness of the hexapod rig was determined to be about 170 kN/mm. The stiffness of the UTM could not be reliably determined, however it was estimated to be significantly lower than the stiffness of the hexapod. A more detailed description of the DLR buckling facility can be found, e.g., in [4]. On all three test rigs, the shells were first mounted in a fully clamped manner on both ends, while additional tests were carried out on the Hexapod with eight shells using a simple support at the top (see Fig. 2).

On the Hexapod test rig, lateral forces occurring during the experiments were measured via a 6 dof load cell and the axial compression and possible tilting were recorded via three optical displacement sensors. Furthermore, the strain was measured with 6 strain gauges arranged around the circumference. An overview of the utilised measurement technology and the test setup at the Hexapod test rig is shown in the right picture of Fig. 3.

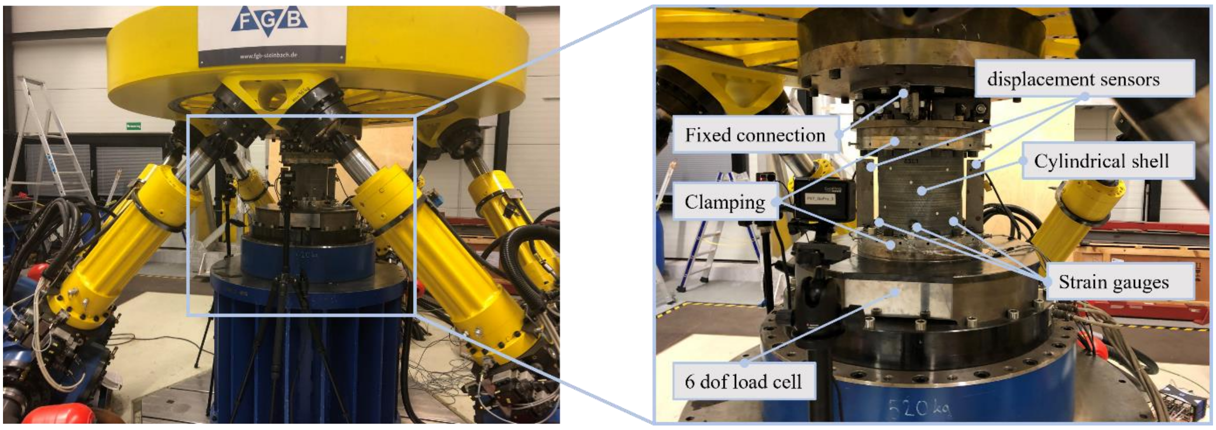

Figure 3: Test setup at the TUHH Hexapod test rig for the experimental campaign in [33]

The box plot in Fig. 4 depicts the buckling loads of the experiments with a fixed connection at both shell ends on the Hexapod test rig. Each shell was loaded displacement controlled in a quasistatic manner at a speed of 2.7 mm/min until buckling a minimum of 6 times in this configuration. Particularly noticeable is the large scatter and comparatively low buckling loads of Z1L1, Z2L1, Z3L1 and Z3W2. As already described in [33], the connection to the test rig shifted slightly during these tests.

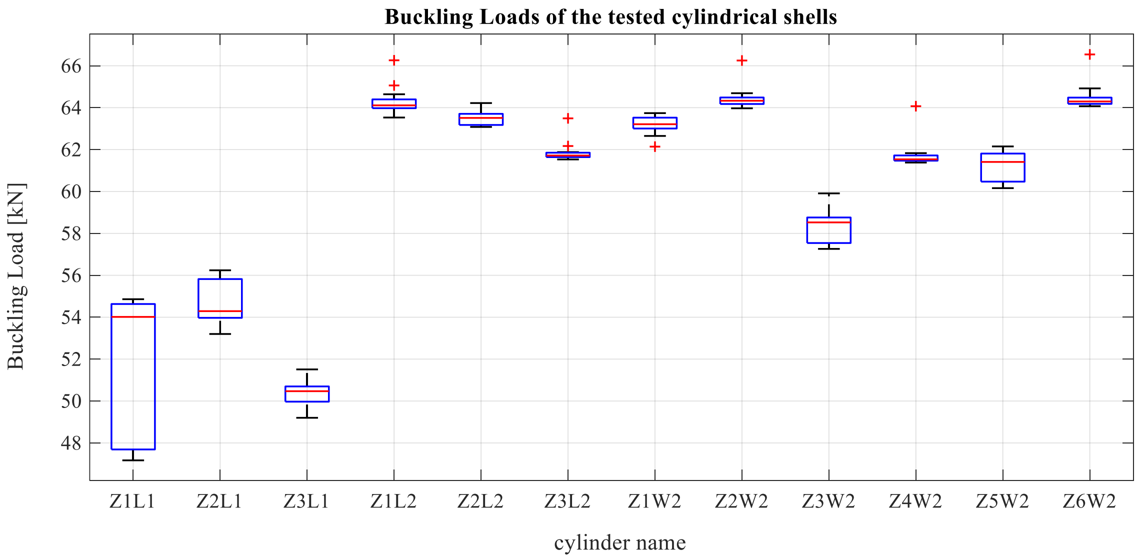

Figure 4: Box plot of experimental buckling loads from [33]

The occurring lateral forces were measured for all buckling tests and indicated in magnitude and direction. The same applies to the tilting of the upper shell edge in the pre-buckling range. The publication [33] also shows how different boundary conditions and test rigs affect the buckling load.

Therefore, the test rig boundary conditions and the utilised setup should always be documented. The comparison of the test rigs also showed an influence on the development of the buckling load. In particular, the low stiffness of the universal testing machine leads to a degradation of the cylinders. Furthermore, the large sample size makes it possible to deduce the results of cylinders Z1L1, Z2L1, Z3L1 and Z3W2 as outliers. All these experimental results were published in a peer reviewed journal, which is open access, so that the experimental data are easily available to other researchers. All further descriptions of the experimental procedure and results can be found in this publication [33]. The Fourier coefficients of the geometric imperfections of the tested shells will be made accessible in a further publication. Finally, the shells investigated in this study and the gathered data were added to the previously described database of buckling tests with cylindrical composite shells under axial compression [20].

5 DISCUSSION

The careful documentation of test conditions and results in the exemplary study according to the proposed guidelines aided not only in the qualification and quantification of influences on the buckling load, but also in the validation of a high-fidelity model according to the NASA specification in [1]. This was achieved by including the measured geometry, the determined material properties and the geometric imperfections, as well as the test rig boundary conditions, measured lateral forces and tilting of the shells into the numerical model. Even though the buckling loads of the first test series were found to be outliers due to imperfect connection to the test rig, the data gathered from these tests proved to be valuable for model validation and in adding to the sample size of the different influence factors measured. Consequently, while such data need to be reviewed critically, they should nonetheless be published alongside the other test results.

Utilising a 6 dof load cell to record all occurring loads proved to be of great use in determining the influence of the test rig boundary conditions, as it was found that significant lateral loads only occur in case of a simply supported connection. Similarly, the data from the circumferentially distributed optical sensors support the hypothesis that in experimental campaigns, fully clamped connections are preferable, as tilting angles of up to 0.04° were measured when using the simple support. Cylindrical composite shells, as discussed in [7] and [32], can in some cases exhibit high sensitivity to such loading imperfections that induce an inhomogeneous stress state within the shell. Hence, it seems to be of significant importance to record occurring imperfections in load introduction.

The results achieved in this study and the success in validating a numerical model based on the documented and published data thus further support the proposed guidelines as a means to generate a transparent and utilisable basis of experimental data on buckling of composite shells. The research area of buckling critical composite shells includes not only cylinders, but also conical and spherical shells as well as panels and a variety of other geometries under different load cases. Thus, while the presented recommendations are phrased primarily with respect to cylindrical shells under axial compression, it stands to reason that they are equally applicable to other geometries and load cases.

6 CONCLUSION AND OUTLOOK

In this contribution, a set of recommendations for conducting buckling tests with composite shells and the publication of experimental results was derived, to serve as a guideline for future test campaigns in order to increase consistency and comparability of the data available in literature. A comprehensive database of the existing data of buckling experiments with cylindrical composite shells in axial compression was compiled and analysed with respect to the quantity and quality of published data. This database is available on the open-access repository Zenodo.org and will be updated as new experimental studies are published.

A number of well-known design approaches for composite shells were analysed regarding the data required for their application. In addition, the necessary experimental data in the validation of numerical models in general, as well as for the validation of new design approaches were discussed. Based on the analyses, a number of recommendations were derived and summarised in the aforementioned set of guidelines. An experimental campaign with 12 cylindrical CFRP shells was then carried out and published according to the postulated guidelines.

It could be shown that following the guidelines suggested in this contribution was significantly beneficial not only to the quality of the test results, but also to the consequent analysis and interpretation of the generated data, thus demonstrating the validity of these guidelines.

Looking forward, while the value of the developed guidelines was shown in the exemplary study, it is necessary to review in future test campaigns whether this set of recommendations does indeed cover the documentation of all information required for the considered use cases. Finally, as elaborated previously, the geometric imperfection data from the presented exemplary study have not been published yet. However, in accordance with the suggested guidelines this will be done in a following publication.

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